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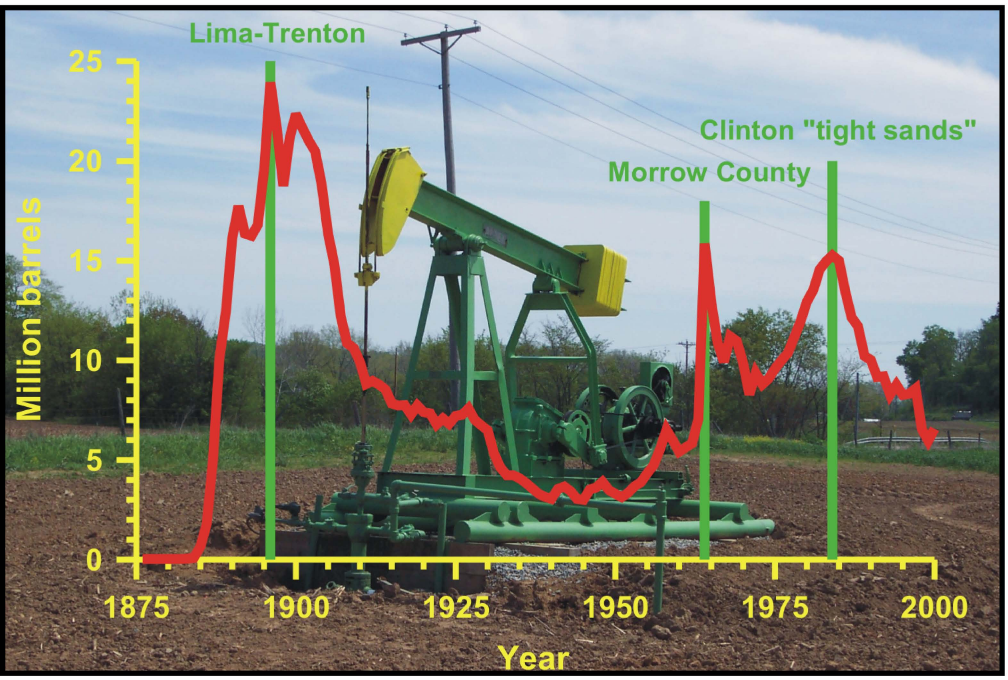

BPRC REPORT No. 21

by
C.J. van der Veen

2006

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The cover photo shows the Torrens #2-3208 well in Washington Township, Licking County, OH. (May 5, 2006).

ABSTRACT

It is often said that we learn from our mistakes. This may be true for individuals, but collectively, humanity repeatedly continues to exhibit collective amnesia and, by ignoring past events – willfully or not – the same mistakes continue to be made. A case in point may be our continued dependence on and consumption of fossil fuels, most notably oil and natural gas. Since the discoveries of oil fields in the upper mid-west of the United States and in southern Ontario, the world economy has become truly dependent on this black gold, led, of course, by a handful of oil-thirsty industrialized nations. Yet most western consumers appear to have little concern about the available resources and how limited these resources are – much like in the early days of the American and Canadian oil boom. Recoverable oil reserves are limited – certainly the end of cheap oil is in sight, if not here already. This may not necessarily imply the end of civilization as we know it, but surely the decline in world oil production will necessitate changes in our way of life and thinking. Perhaps most surprising is the fact that many smaller communities have experienced their local "peak oil" and gone from boom to bust – yet, many people, including most politicians, continue to be optimistic and hope for some magical solution to our problems. As argued in this report, what has happened on smaller scales to the towns of Petrolia, PA, ON, TX, CA, and to many other communities in the original heartlands of oil exploration, is bound to replay on the world stage. This time around, however, there may not be an easy way out.

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INTRODUCTION

From the humble beginnings of using wood to fuel fires for cooking, heating, and scaring animals away, to today's nuclear power plants and congested highways, the history of mankind is characterized by an almost obsessive quest to harness ever-growing quantities of energy. Only as recently as 5000 years ago, ancient civilizations started using energy sources other than the sun and wood, starting with wind power to sail the seas and travel to new places. Windmills and water-powered mills were used around 2500 years ago to grind grain, pump water from low-lying areas, and run sawmills. It was not until the invention of the steam engine by James Watt around 1770 that the world became truly mechanized, allowing for the rapid industrialization and mass production of goods with consequent escalating energy consumption.

Nature's windfall that made explosive growth possible was the discovery of vast reservoirs of oil and natural gas, first in North America, followed by the Middle East, the North Sea platform, and in many other places around the globe. Oil-derived products had been in use since 3000 BC when Mesopotamians used *rock oil* as architectural adhesives, caulking for ships, medicines, and roads. Around 2000 BC, the Chinese were refining crude oil for use in lamps and for heating their homes. Today, oil is used primarily for transportation purposes, with one barrel (42 U.S. gallons) of crude oil producing about 20 gallons of gasoline, 7 gallons of diesel fuel, and 4 gallons of jet fuel. Other applications and products make up about 25% of oil derivatives. It is important to realize that oil products permeate almost every aspect of our daily lives, as illustrated in Table 1, which lists oil-derived products for the 1997 refinery year. World consumption in 2005 amounted to slightly more than 900 barrels per second – replacing oil as the fuel of choice will be a daunting task indeed.

Petroleum – oil and natural gas – consists of hydrocarbons, which are chain-like, and ring-like molecules made of carbon and hydrogen atoms. Natural gas contains one to four carbons per molecule, whereas gasoline contains five to ten carbons per molecule. High-viscosity oil derivates such as tar contain more than 40 carbons per molecule. Oil is a unique substance that contains large amounts of energy per volume, and it can be distributed easily over great distance via pipe lines, ships and tanker trucks, using regular unpressurized metal tanks at air temperature (Kunstler, 2005, p. 31). Yet, at the same time, oil is a scarce resource that formed during the geologic past, under a special set of circumstances. Most introductory geology textbooks discuss how fossil fuels were formed, and a brief summary from Marshak (2005, p. 441-445) highlights the special conditions required for oil and gas fields to develop.

Motor Gasoline	45.70%	Kerosene	0.40%
Distillate Fuel Oil	22.50%	Illumination	
Diesel Fuel		Space Heating	
Home Heating Oil		Cooking	
Refinery Fuel		Tractor Fuel	
Industrial Fuel		Special Naphthas	0.30%
Kerosine-Type Jet Fuel	10.30%	Solvents	
Residual Fuel Oil	4.70%	Paint Thinner	
Boiler Fuel		Miscellaneous Products	0.30%
Refinery Fuel		Absorber Oil	
Bunker Fuel		White Machinery Oils	
Wood Preservative		Cutting Oils	
Petroleum Coke	4.60%	Candymaking, Baking Oils	
Carbon Electrodes		Technical Oils	
Fuel Coke		Medicinal Salves. Ointments	
Electric Switches		Petroleum Jelly	
Liquefied Refinery Gases	4.60%	Acetic Acid	
Petrochemical Feedstocks		Sulfuric Acid	
Space Heating, Cooking		Fertilizers	
Synthetic Rubber		Waxes	0.20%
Still Gas Refinery Fuel	4.40%	Used for:	
Asphalt and Road Oil	3.20%	Fruits, Vegetables	
Paving		Candy, Chewing Gum	
Roofing		Candles, Matohes	
Waterproofing		Crayons, Pencils	
Petrochemical Feedstocks	2.90%	Sealing Wax	
Alcohols, Resins, Ethers		Canning Wax	
Fibers			
Medicines			
Cosmetics			
Lubricants	1.20%		
Lubricating Oils			
Greases			
Transmission Oils			
Household Oils			
Textile Spindle Oils			

TABLE 1. Petroleum products and uses in percent refinery yield for the year 1997. *Based on data from the Energy Information Administration.*

Whereas coal derives from swamp vegetation that is gradually buried and turned into solid rock, the primary sources of the organic chemicals in petroleum are plankton and algae. Plankton are microscopic plants and animals that float in seas and lakes. While alive, plankton and algae use sunlight for growth and sustenance, thereby effectively storing solar energy in their biomass. When plankton and algae die, the remains settle on the lake or sea floor. However, because the cells are so small (typically with a diameter of 0.5 mm), deposition only occurs in quiet-water

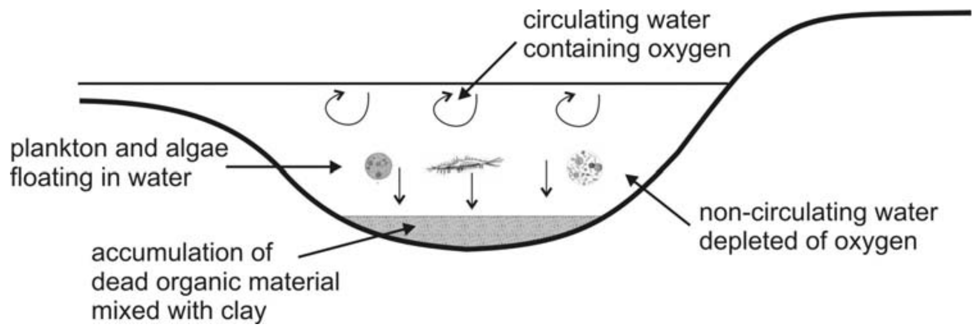

FIGURE 1. Sedimentary environment favorable for deposition of organic rich material on a basin floor. *From: Rogers and Feiss (1998).*

environments in which clay is usually deposited as well. Thus, over time, an organic-rich muddy "ooze" will form. Usually, organic material is oxidized by bacteria and nutrients are released back into the water, thus the ooze can only be preserved in water that is deprived of oxygen – typically shallower basins at the edges of the world's oceans (Figure 1). As the ooze is buried by sediment, the organic ooze will lithify and turn into black organic shale. This shale contains the materials from which the hydrocarbons in oil and gas eventually form, and it therefore is referred to as the *source rock*. Over periods of perhaps millions of years, the organic shale is buried more and more deep and when it reaches a depth of 2 to 4 km, temperature and pressure are high enough to initiate chemical reactions that slowly transform the organic material in the shale into waxy molecules called *kerogen*. If burial continues and the ambient temperature reaches 90 ^{o}C or above, the kerogen molecules are broken down to form oil and natural gas. However, if the temperature rises above 160 ^{o}C, the remaining oil is broken down to form natural gas. Where temperatures reach above 250 ^{o}C, hydrogen material is stripped away completely, and organic material is transformed into graphite. Thus, there is a rather narrow range of temperatures (the "oil window") at which the organic material in the source rock is turned into oil. The depth at which the oil window is open depends on the geothermal gradient, that is, how rapidly the temperature increases with depth below the surface, but a typical depth range is 2 – 6 km below the Earth's surface.

Oil and gas are not stored in large subterraneous caverns but, instead accumulate in *reservoir rocks* – typically containing ~5% of oil or gas. Reservoir rocks must be porous, with open spaces to store the oil and gas, and permeable, meaning there must be small channels through which the oil and gas can flow from one pore space to another. Poorly cemented sandstone makes an excellent reservoir rock. Because oil and gas are lighter than water, they will slowly migrate towards the Earth's surface, provided there are enough pathways, such as fractures and cracks, leading upward, much like migration of groundwater. Of course, this upward migration will

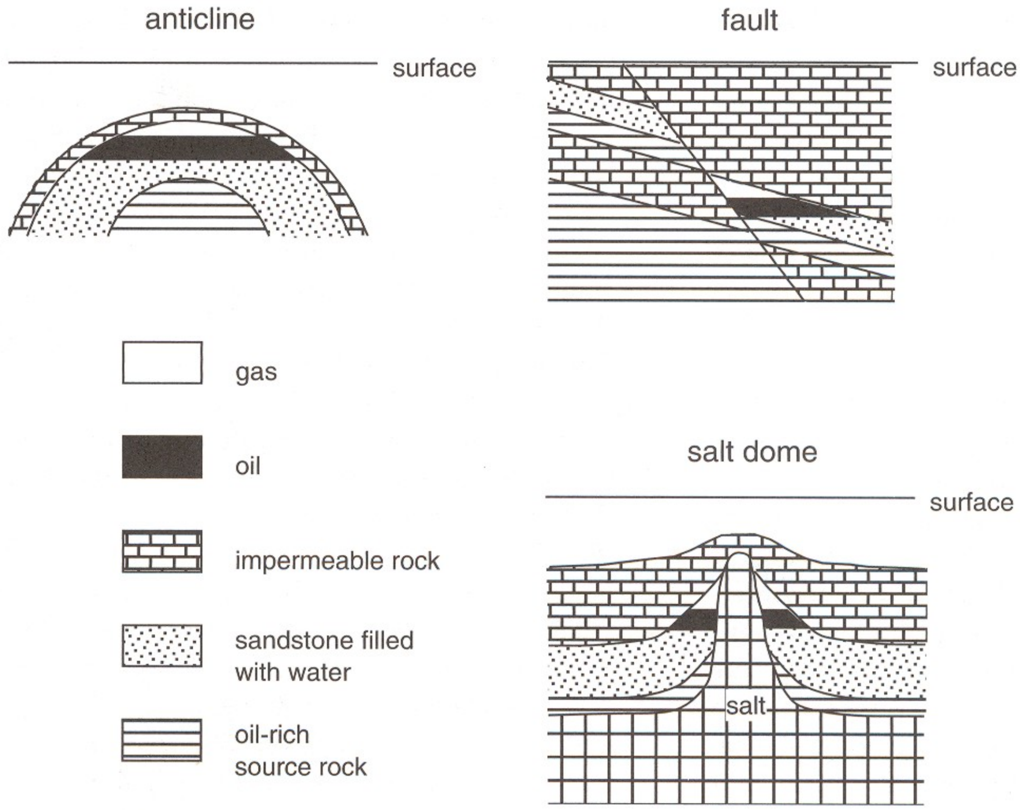

FIGURE 2. Different types of oil traps. In an *anticline trap*, oil and gas rise to the crest of the upward-folded layer of reservoir rock until further upward migration is prevented by an impermeable cap or seal rock. In a *fault trap*, oil and gas collect in tilted strata of reservoir rock adjacent to the fault. In a *salt-dome trap*, the oil and gas collects in tilted strata on the flanks of the impermeable salt dome. Salt domes occur where the sequence of strata contains a thick layer of salt, deposited when seawater was covering a shallow basin. Because salt is not as dense as sandstone or shale, it tends to rise up through overlying strata. Once the salt starts to rise, the weight of surrounding layers squeezes the salt out of the salt layer and up into a growing bulbous salt dome. *From: Rogers and Feiss (1998).*

continue until the oil and gas reach the surface, where it leaks away at an oil seep. Deffeyes (2005, p. 15) estimates that as much as 90% of oil makes its way to the surface as oil seeps, leaving a mere 10% to become trapped in reservoir rocks. To prevent this seepage, the reservoir rock must be overlain by an impermeable layer of seal or *cap rock* (e.g. shale, salt, or unfractured limestone) that prevents further upward migration. Both the reservoir and cap rock must be arranged such that the oil or gas collect in a relatively restricted area. Some examples of oil and gas traps are shown in Figure 2. Note that because gas is lighter than oil, it will tend to collect on top of the oil layer.

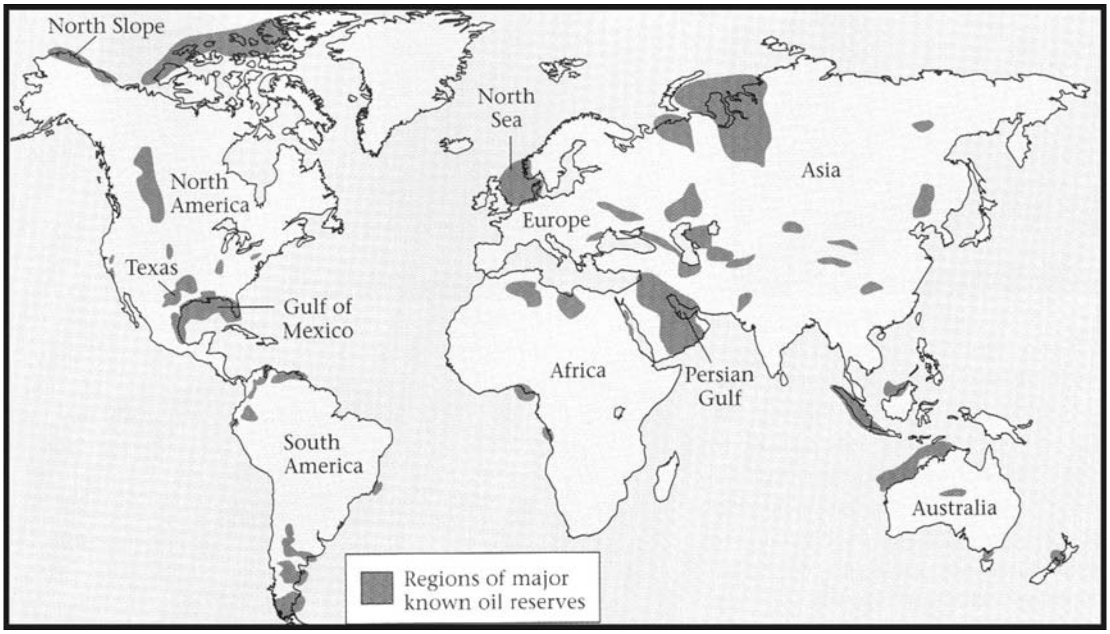

FIGURE 3. Distribution of discovered major oil fields around the world. *From: Marshak (2005).*

Summarizing the conditions under which oil fields can develop: deposition of organic materials in undisturbed and oxygen-deprived waters, burial to depths where temperatures fall within the oil window, and the presence of reservoir rocks with overlying cap rocks, to trap the oil and gas in a small geographic region. So, what if one or more of the conditions is not met? There will be no oil. In the words of Deffeyes (2005, p. 16), “Nature has a funny way of grading exams. You answer seven questions, your grade on the overall exam is the lowest grade that you got on any one of the seven.” Because all conditions must be favorable, few places on Earth are blessed with oil riches (Figure 3). Clearly, the Middle East is well ahead of the rest of the world, with the bulk of the world’s remaining proven reserves occurring in an area not much larger than the U.S. Pacific Northwest (Figure 4).

In essence, fossil fuels represent highly concentrated reservoirs of solar energy, captured by plants and small animals and stored in biomass, which has subsequently been turned into either coal, or oil and natural gas. This conversion is an extremely slow process, probably requiring millions of years. For time scales of human interest (centuries or so), oil and gas reserves must be viewed as finite. That is, there is a limited quantity of these resources, and once used they will be gone forever. To fully appreciate this point and its implications, it is necessary to consider the laws of thermodynamics.

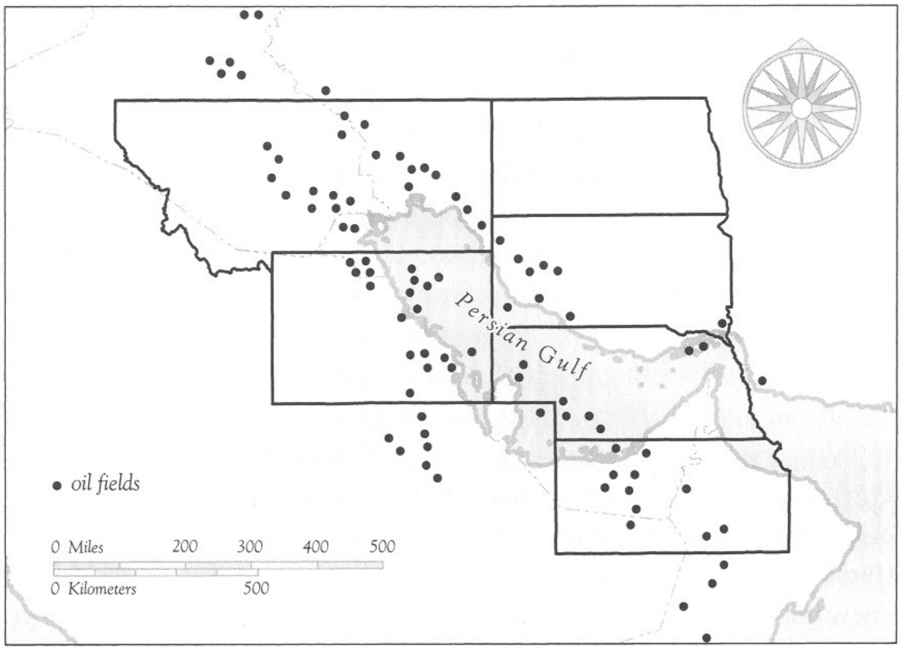

FIGURE 4. Distribution of oil fields in the Middle East compared to the size of the U.S. Pacific Northwest. *From: Deffeyes (2005).*

The first law of thermodynamics states that energy cannot be created or destroyed. How then, one might ask, can modern society face impending energy shortages? The answer lies in the second law of thermodynamics, which states that in every natural process, the entropy remains constant or increases – there is no process possible for which entropy decreases. For most readers, entropy is a nebulous concept from physics. Indeed, the formal definition of entropy introduced by Ludwig Boltzmann is difficult to explain without delving into statistical thermodynamics, but a workable interpretation is that entropy represents the degree of disorder or randomness. As an example, consider the mixing of hot and cold water in an isolated container that does not allow heat exchange with the outside. We might take advantage of the flow of heat from the hot water to the cold water to generate some mechanical energy, but once the water in the container has mixed and gained a uniform temperature, the opportunity to convert heat into mechanical work has been lost, and irretrievably so. The process is irreversible because the second law of thermodynamics prevents the water from unmixing and separating into hot and cold portions, even though the total energy of the unmixed and mixed water is the same. Thus, what has been lost in the mixing process is not energy itself, but the opportunity to convert a portion of the heat flow into mechanical work. Stated simply, when entropy increases energy becomes more unavailable for human applications.

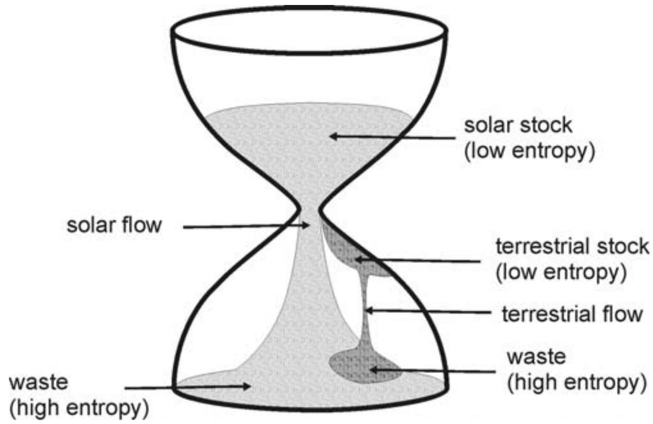

FIGURE 5. The "entropy hourglass." Low-entropy solar energy flows from the upper reservoir to the lower chamber where it is turned into useless high-entropy energy. Only the flow of solar energy can be converted into mechanical energy or work. Over geologic time, some of the solar energy was stored in the form of fossil fuels, representing a limited but low-entropy stock of energy that can be utilized at any desired rate until, of course, this source becomes depleted. *From: Daly (1996).*

An excellent way to visualize this uni-directional flow of energy is by means of the "entropy hourglass" analogy, based on the work of the economist Nicholas Georgescu-Roegen (1971) and discussed in Daly (1996, p. 29-30). Referring to Figure 5, the hourglass is a closed system with no sand (energy) entering or leaving the hourglass. Further, within the glass, sand is neither created nor destroyed – analogous to the first law of thermodynamics. Third, there is a continuous flow of sand from the top chamber (the Sun) to the bottom reservoir (the Earth). Once this sand collects in the bottom chamber, it has used up its potential to do work and thus represents high-entropy energy that cannot be converted into mechanical energy. Only sand in the upper chamber has the potential to fall and represents low entropy energy available for conversion to mechanical energy or work. However, as sand continues to flow from the upper to the lower chamber, the amount of available useful energy decreases as more sand accumulates in the lower chamber (i.e. the entropy increases). The rate at which sand is transferred from the upper to the lower chamber is governed by the constricted middle of the hourglass and this represents the rate at which energy can be converted on a sustainable basis. Over geologic time, some of the falling sand got stuck on the upper part of the inside wall of the lower reservoir, before falling all the way to the bottom. This sand represents the terrestrial stock of high-energy low entropy fossil fuels which humanity is currently tapping into and converting into high-entropy useless energy. As pointed out by Daly (1996, p. 30), there is an important difference between these two sources of energy: solar energy is almost unlimited ("stock-abundant") but the rate at which it arrives on Earth is limited, whereas the terrestrial source of stored solar energy is rather small ("stock-limited") but can be mined at any rate we choose until the stock has been depleted.

The importance of the irrevocable qualitative degradation of free into bound energy cannot be stressed enough. Quoting Georgescu-Roegen (1971, p. 6),

> in rounding out this picture, we should note that the full meaning of the Entropy Law is not that the qualitative degradation occurs only in connection with mechanical work performed consciously by some intelligent beings. As exemplified by the sun's energy, the entropic degradation goes on by itself regardless of whether or not the free energy is used for the production of mechanical work. So, the free energy of a piece of coal will eventually degrade into useless energy even if the piece is left in its lode.
>
> There are some good reasons why I stress (here as well as in some chapters of this volume) the irrevocability of the entropic process. One reason interests the economist in particular. If the entropic process were not irrevocable, i.e., if the energy of a piece of coal or of uranium could be used over and over again ad infinitum, scarcity would hardly exist in man's life. Up to a certain level, even an increase in population would not create scarcity: mankind would simply have to use the existing stocks more frequently. Another reason is of more general interest. It concerns one of man's weaknesses, namely, our reluctance to recognize our limitations in relation to space, to time, and to matter and energy. It is because of this weakness that, even though no one would go so far as to maintain that it is possible to heat the boiler with some ashes, the idea that we may defeat the Entropy Law by bootlegging low entropy with the aid of some ingenious device has its periodical fits of fashion. Alternatively, man is prone to believe that there must exist some form of energy with a self-perpetuating power.

In the 35 years since Nicholas Georgescu-Roegen wrote these words, it appears that humanity has not heeded his words and continued full-blast on the unsustainable path of growing energy consumption, with little apparent concern about the available resources and how limited these resources are. This report provides a brief overview of the history of oil exploration, with emphasis on Ohio and surrounding regions, and demonstrates how many smaller communities have experienced their local "peak oil" and gone from boom to bust. Rather than learning from these lessons from the past, many people continue to be optimistic, denying the world is nearing it's peak in oil production, and hoping, if not expecting, some magical "fix" will solve the world's energy problems as we run out of oil. What has happened on smaller scales to the towns of Petrolia, PA, ON, TX, CA, and to many other communities in the original heartland of oil exploration is bound to replay on the world stage. This time around, however, there may not be an easy way out.

BIRTH OF THE WORLD'S OIL BOOM

In 1858, James Miller Williams dug what was to become North America's first commercial oil well near the town of Black Creek, Ontario. The name of this town – a year later renamed Oil Springs – referred to the patches of black and sticky crude oil named "gumbeds" (Figure 6) and to the oily residue in the local creek. For many years, native peoples had used this oil for medicinal and ritual purposes but it was not until Charles and Henry Tripp of Woodstock, Ontario,

FIGURE 6. "Gumbeds" at the National Oil Heritage Museum, Oil Springs, Ontario.

incorporated the International Mining and Manufacturing Company in 1854, that the petroleum source was exploited commercially. Products ranged from caulking for ships to asphalt and varnishes, and, of course, burning fuel. Shortly thereafter, however, the Tripps were forced to sell their company to James Miller Williams who took commercial development a step further by digging a well which, in 1858, produced 50 barrels of oil per day. Both the Tripps and Williams were recognized internationally for their oil production and refining achievements. The Tripps won honorable mention at the Paris Exhibition of 1855 for their asphalt, and Williams won two gold medals at the London Exhibition in 1852.[1]

In the spring of 1861, with a working capital of only $50, Hugh Nixon Shaw set up a spring-pole rig (Figure 7) and began to drill along the banks of the creek at Oil Springs, continuing through the winter months of 1861 and 1862. By that time, Shaw had used up not only his own credit but that of his two workers – Hugh Smiley and John Coryell – as well, and on January 15, Shaw decided that he would drill for one more day before admitting defeat. As fate would have it, he struck oil on January 16, 1862, and the noise of the gusher exploding caused the earth to shake. At the time, no one knew how to turn off the gusher and it was estimated that more than

[1] Based on information obtained at the Oil Museum of Canada, Oil Springs, Ontario, September 2004

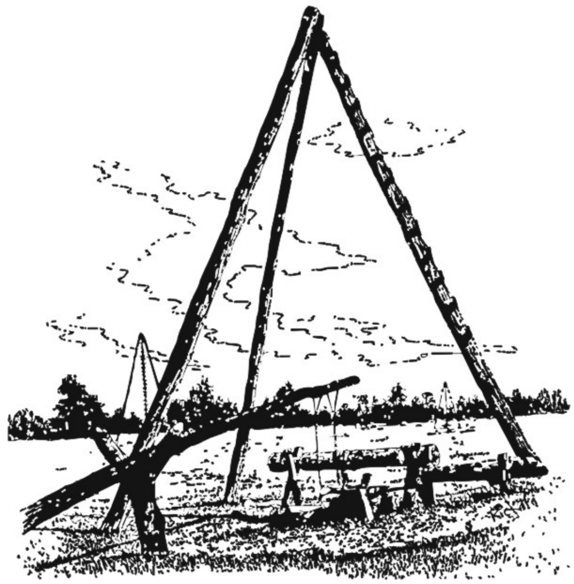

FIGURE 7. Spring-pole rig used by Hugh Nixon Shaw to drill for oil in southern Ontario. *From: Black Gold: Canada's Oil Heritage, http://collections.ic.gc.ca/blackgold/frames.html*

100,000 barrels of oil were wasted before the flow could be stopped. For four days, oil from this well gushed as high as the treetops, flooding the hollow where the well was located, and flowing down the local creek to the St. Clair River and ultimately into Lake St. Clair.[2]

The oil boom really took off after Shaw's success, and the town of Oil Springs expanded rapidly to a population of 2000 by 1864, boasting eight general stores, five blacksmith shops, five hotels, a telegraph office, a daily newspaper, and many refineries to process the oil from 300 wells in the region. Among other notorious achievements of this frontier town were the first planked main street in Canada, and the only kerosene-lighted main road anywhere. Unfortunately, the boom soon became a bust as oil production fell and prices dropped. By 1866, the population of the town had fallen to a mere 300. Exploitation of the oil resources was rather inefficient as at times the creek basin was filled with crude oil up to three feet thick.

Oil production in southern Ontario soon shifted to the nearby town of Petrolia, which blossomed into Canada's "Victorian Oil Town" and became the oil capital of the region. By the 1880s, countless wooden framework towers dotted the countryside. Canadian oil was in high demand and intoxicated by the town's success and by the smell of petroleum in the air, the locals believed the success story would never end. However, the wells soon started to dry up, and by

[2] Based on: Black Gold: Canada's Oil Heritage, http://collections.ic.gc.ca/blackgold/frames.html

FIGURE 8. The Phillips well, on the right, and the Woodford well, on the left. Located in the middle of Oil Creek Valley (note the river at the right of the photograph), these two wells showed the early promise of the oil regions in Pennsylvania. The Phillips well was the most productive ever drilled to date, flowing initially at 4,000 barrels per day in October of 1861. The Woodford well came in at 1,500 barrels per day in July, 1862. Note the wooden tank collecting the oil in the foreground, as well as the many different sized barrels in the background. At this time, barrel size was not yet standardized, which made terms like "Oil is selling at $5 per barrel" very confusing. *From Pennsylvania Historical & Museum Commission, Drake Well Museum Collection, Titusville, PA.*

1894 only five refineries were operating in this once lively and bustling town. Currently, there are still wells operating at Petrolia and in the Lambton oil field, although by today's standards, the output is rather modest.[3]

Meanwhile, south of the border, in western Pennsylvania, oil fever had blossomed into full bloom as well. In August, 1859, "Colonel" Edwin Drake struck oil along Oil Creek, just south of Titusville.[4] As a result of Drake's discovery, boomtowns sprang up in the region as derricks replaced trees and people flocked to the region in search of liquid gold (Figures 8 – 10). In their quest for oil, the newly-arrived explorers gave little regard to the natural environment or showed much concern about preserving the precious petroleum resources. Throughout the valley, oil and mud mixed, making roads nearly impassable and covering the creek with oil. The euphoria was

[3] Based on information from the En-Ar-Co/White Rose site, <http://allcanadiancompany.com/pg2.html>
[4] According to the Pennsylvania Department of Conservation and Natural Resources, this discovery marks the birth of the world's oil industry. That view is challenged by information provided by the Oil Museum in Oil Springs, as noted above. For the present discussion, the issue of "who was first" is irrelevant.

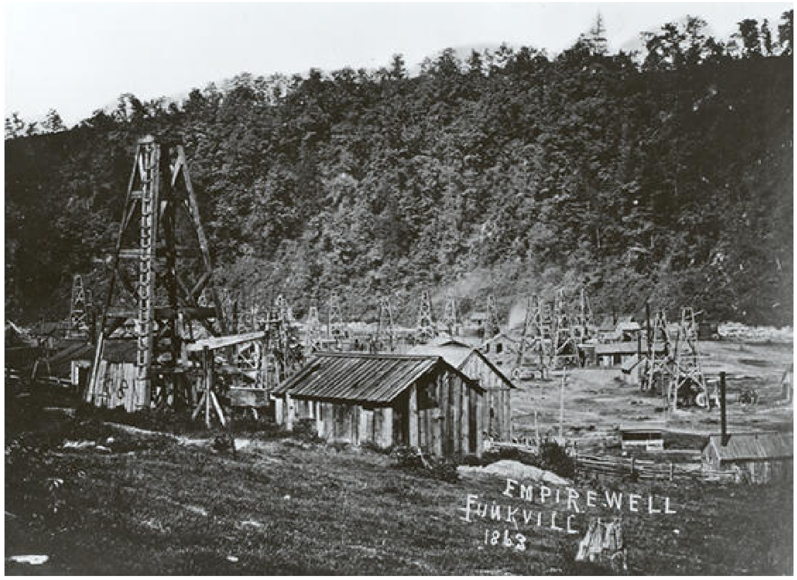

FIGURE 9. The first great flowing well in the history of the oil industry was the Empire well on Funk Farm. Completed in September, 1861, it initially flowed at 3,000 barrels per day. This well also illustrated the turbulent nature of the oil industry in these early days. With an extra 3,000 barrels of oil flooding the market each day, the price of oil plummeted to 10 cents a barrel. *From Pennsylvania Historical & Museum Commission, Drake Well Museum Collection, Titusville, PA.*

FIGURE 10. Triumph Hill held the highest density of wells in the oil regions. In this photograph alone, more than 100 derricks can be counted. These wells produced hundreds-of-thousands of barrels of the purest oil in the region, and this photograph is an excellent example of the overproduction of many fields in the area. Years later, it was discovered that putting wells too close together actually *decreases* the amount of oil that could be taken from the ground. *From Pennsylvania Historical & Museum Commission, Drake Well Museum Collection, Titusville, PA.*

short-lived, however, and by 1871 production was dwindling and drillers and explorers moved on to other areas in their endless search for oil.[5]

No doubt encouraged by the oil mania sweeping the nation, in the 1880s, the General Assembly of Ohio appropriated funds for a survey for oil and gas under the direction of Edward Orton Sr., a prominent geologist and first President of The Ohio State University (1873 – 1881). Orton (1889, p. 522) described the discovery of the first gas deposits as follows:

> The first discovery on record of inflammable gas in the Findley field was made while digging a well, three and a half miles south of the court-house, in October, 1836. But from the known facts as to its occurrence it is scarcely possible that its presence should not have been known to the earliest occupants of the country.
>
> The discovery was made under the following circumstances: A well was being dug on a farm in the northwestern quarter of section 5, Jackson Township, which was at the time owned by one Aaron Williamson. The diggers had reached a depth of ten and a half feet in the drift and water began to appear. They were just then called to supper, but fearing that the well would fill with water and that the banks would cave in if left, they returned in the early evening with lighted torches to complete their work by laying the wall, the stone for which had already been drawn to the spot. Lowering a lighted torch into the excavation to ascertain its condition, they were startled by a violent explosion, and a flame of considerable volume was afterwards found burning from the surface of the water below. The labor spent in the excavation was counted lost and supply of water was sought at another point. The burning well attracted a good deal of attention in the neighborhood. The flame lasted for several months, but was at last extinguished by the rains and snows of early winter and the well was afterwards filled up. Similar experiences soon followed in other wells and in like excavations, and these were especially common within the village limits of Findlay. From this time it was known that inflammable gas, explosive also when mixed in certain proportions with air, was likely to be found whenever the limestone floor of the country was approached. The cases in which this oftenest occurred were in the digging of wells, cisterns, and sewers in the town of Findlay.
>
> There were other surface indications at hand that were equally significant. From the springs that issued from the limestone rocks in the valleys gas was constantly escaping in considerable quantities. It was known that this gas could be lighted at any time and that it would often continue to burn for hours without interruption. Experiments in lighting were constantly repeated, and not a child grew up in the neighborhood without becoming acquainted with its manifestations.

Orton's survey located oil and gas deposits in northwestern Ohio, sparking a tremendous oil boom near the cities of Findlay and Lima.[6] Once again, the supply of oil and gas appeared to be endless and, as a result, much of the resources were wasted. The city of Findlay, in Hancock County, offered free gas to any factory built there and lit the streets with gas torches night and day. History repeated itself, and by 1900, a mere 24 years after it began, the fields were depleted

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[5] Based on information about the history of Oil Creek State Park provided by the Pennsylvania Department of Conservation and Natural Resources, <http://www.dcnr.state.pa.us/stateparks/parks/oilcreek.aspx>

[6] According to the Ohio Oil and Gas Association, the claim for the first drilled oil well should go to Ohio because in 1814, a saltwater well driller discovered oil at a depth of 475 feet in Noble County; <http://www.ooga.org/PDFs/Industry%20Overview%20Document.pdf>

and the great northwest Ohio oil boom collapsed (Dexter, 1979). Many Ohio towns, including first Findlay and Lima, and later Macksburg (Washington County) and Toboso (Licking County), experienced the cycle of prospering communities during the height of oil production, followed by economic hard times as the wells dried up (ODGS, nd). As before, little regard was given to environmental concerns, and, frequently, when a well was shot and a gusher developed, area homes and trees might be dripping with a spray of oil. Many local creeks and streams turned black from oil runoff, which could be burned by tossing flaming branches into the streams (Mollenkopf, 1999, p. 103).

Wherever one looks, the story is similar – be it Petrolia, Ontario, Petrolia, Pennsylvania, Petrolia, Texas, or Petrolia, California. In Texas, the Petrolia field (named after the Pennsylvanian town) was discovered in 1904 with a true gusher blowing in on December 17, 1910. Peak production was reached in 1914, when 550,585 barrels were recovered. Decline in production rapidly followed, and discoveries at other oil fields soon overshadowed production at Petrolia, TX. The discovery of natural gas made up for some of the decline in oil production, but by 1921, the field ceased operations altogether.[7]

OHIO'S CRUDE OIL INDUSTRY

As elsewhere, the history of oil exploration in Ohio is one of cycles of "booms and busts." The earliest discovery of oil, in Noble County, dates back to 1814 when a saltwater well driller discovered oil at a depth of 475 feet. It took almost another half century, however, before Ohio's first commercial oil well was placed into production. In late 1859, the first well drilled for the specific purpose of producing petroleum was completed in Mecca Township in Trumbull County. The great oil boom occurred at the turn of the twentieth century with production from the Trenton Limestone in the Lima-Indiana oil and gas fields (Figure 11). At the height of production in 1896, more than 23 million barrels were produced annually. Over the 20 years this boom lasted, the Ohio portion of the Trenton Field produced more than 380 million barrels of oil, making Ohio the nation's leading oil producer from 1885 to 1903 (ODGS, nd).

Starting in 1905, oil production in Ohio fell steadily for almost 50 years, and did not start to increase until the introduction of hydraulic fracturing in 1951. In this process, water is used to apply hydraulic pressure to the oil and gas bearing rock to fracture the rock and create vertical

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[7] Based on information from "Petrolia Oilfield" The Handbook of Texas Online; <http://www.rra.dst.tx.us/c_t/history/clay/PETROLIA%20OILFIELD.cfm>

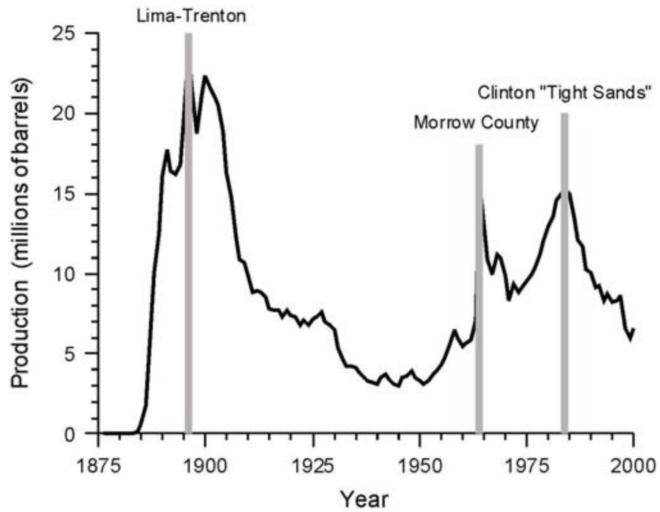

FIGURE 11. Annual oil production in Ohio since 1875. The three peaks correspond to the early production from the Lima Trenton limestone field in northwest Ohio, recovery of prolific oil in the vugular Cambrian Trempealeau dolomite in Morrow County, and recovery from the Clinton sandstones in Fairfield County. *Based on data from the Ohio Department of Natural Resources, Division of Mines (data provided by Larry Wickstrom).*

drainage conduits within the reservoir. These conduits allow the oil to move more freely from the rock pores to the wellbore where it is recovered. As a result of this technique, oil production slowly started to increase (OOGA, nd).

Ohio's short-lived second peak in oil production occurred in the 1960s, when prolific oil was discovered in the "vugular" Cambrian Trempealeau dolomite, primarily in Morrow County. In 1964, approximately 413 wells were completed, and production during that year was more than 10 million barrels. Part of the sudden interest in this oil field may be attributed to the relatively shallow depth of 3000 feet, and the nature of the rock reservoir, with vertical fracturing rendering the oil resources more accessible (Sutton, 1965). By the late 1960s, however, most of the economically viable resources had been depleted and production from this oil field dwindled.

The third period of increased production activity in Ohio occurred during the 1980s, with recovery from the Clinton sandstone in Fairfield County, as well as from the Berea sands and Ohio shale. These fields had been exploited earlier in the century but wells often required nitro-shot stimulation to enhance production, and by the late 1940s, these fields were believed to be economically unattractive. However, rising prices in the 1970s, together with advances in fracturing technology and tax incentives, made the fields once again attractive – that is, until oil prices started to collapse a decade later (OOGA, nd).

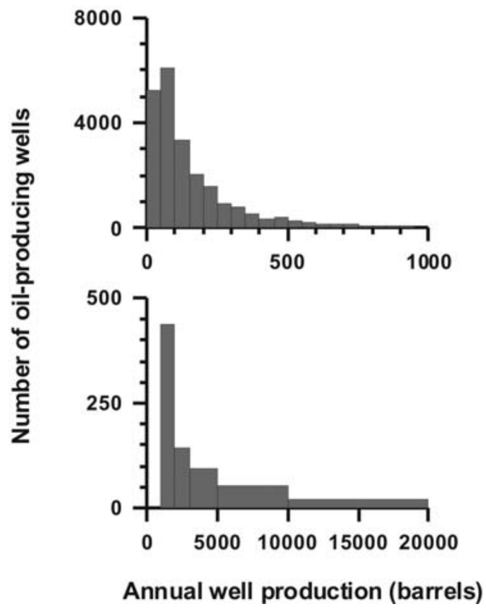

FIGURE 12. Distribution of oil-producing wells in Ohio for 2002. Note the different vertical scales for small wells (annual production less than 1000 barrels; top) and large well (annual production greater than 1000 barrels; bottom). The vast majority of Ohio wells produce fewer than three barrels per day. *Based on data from the Ohio Department of Natural Resources, Division of Mines.*

According to data compiled by the Ohio Department of Natural Resources, in 2002 there were 23,062 oil-producing wells in the state, with a total output of slightly less than 5.6 million barrels, thus averaging 242.5 barrels per year per well. The majority of these wells, however, are operating at the lower edge of profitability, with 87.2% producing less than one barrel per day (Figure 12). Only 25 Ohio wells had an annual production exceeding 10,000 barrels in 2002, with the top producer ("Painter" in Licking County) yielding 34,041 barrels. To put these numbers in perspective, according to Department of Energy annual data, in the year 2001 Ohio's consumption of petroleum-derived products was equivalent to 239.6 million barrels of crude oil. Thus, the state's total oil production amounts to 2.3% of its annual consumption. Total 2002 production per county is shown in Figure 13 and reveals that the center of activity has moved from the northwestern part of the state to more eastern counties. Indeed, few of the counties involved in the early oil boom are currently producing any crude oil.

HUBBERT'S PEAK

Inspection of the oil production graph for Ohio (Figure 11) shows three distinct peaks, each associated with the exploration of a particular oil deposit. This pattern is characteristic for the exploitation or mining of any finite natural resource, be it oil, coal, or diamonds and gold.

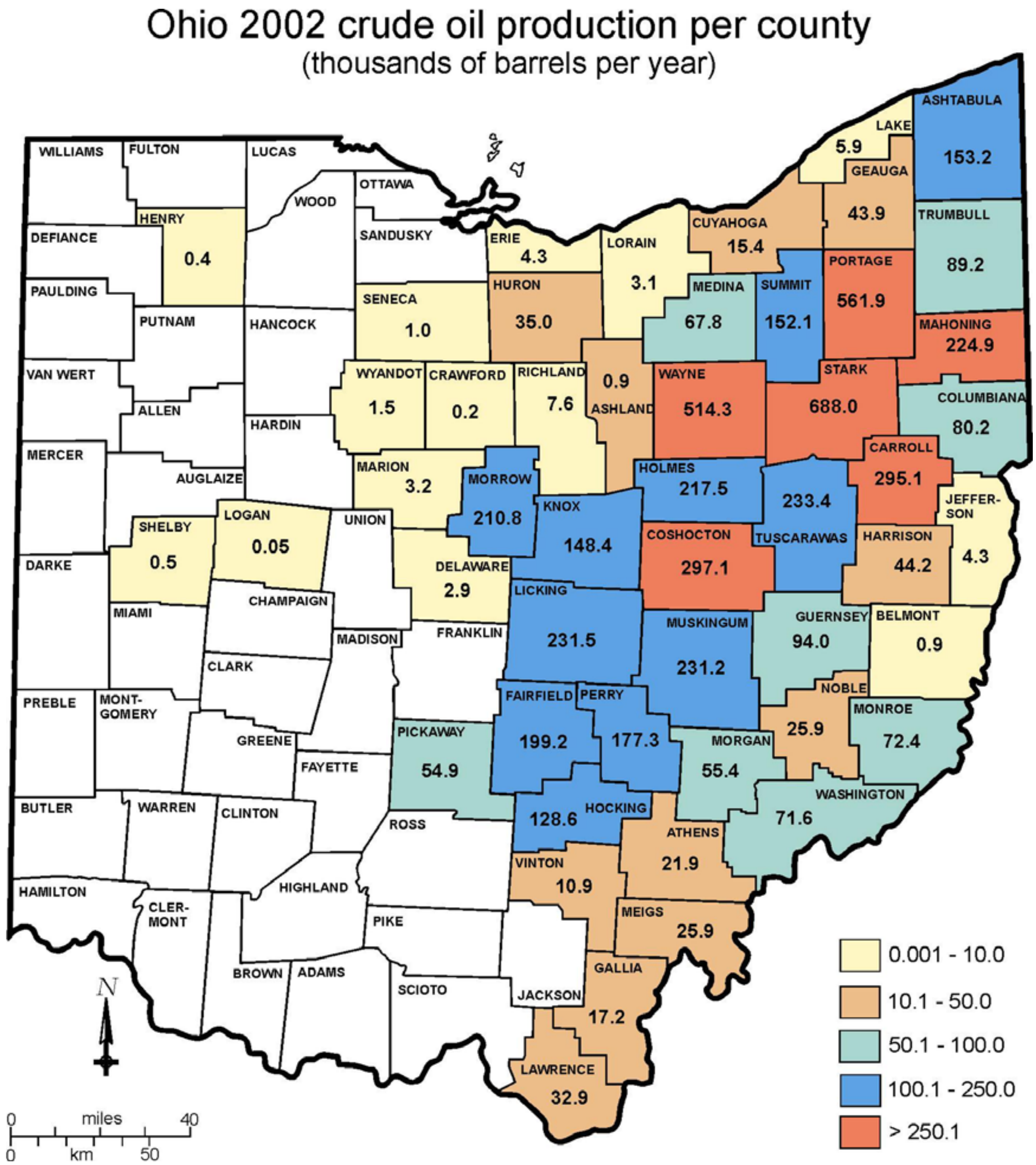

FIGURE 13. Oil production per county (in thousands of barrels per year) for 2002. *Based on data from the Ohio Department of Natural Resources, Division of Mines.*

Following discovery, production rises as the number of recovery sites (wells or mines) rapidly increases and easily-accessible resources are harvested. In the case of oil, initially little effort needs to be expended to retrieve the oil, because reservoir pressures are sufficiently high to drive the oil forcefully to the surface – as evidenced by gushers when a new source is tapped. After some time, however, the pressure drops and more effort is required to bring the oil to the surface. Eventually, production in a field will decline as the rate at which new reserves are being discovered falls behind the production rate. At this point, the larger deposits have been discovered, and what is left are numerous smaller pockets that generally are more expensive to extract, and contain smaller reserves than the larger deposits. Ultimately, production in a region will cease when remaining resources cannot be harvested economically. For oil, primarily used as an energy source, the real factor controlling when a field should be considered depleted is not so much the cost of mining the oil – although this does play some role as during the third peak in Ohio oil production – but when the energy required to extract the last few drops exceeds the energy produced by these last few drops.

As an aside, it may be noted here that production from a gas field does not follow this pattern. This is because gas is sufficiently light to move upward, even when pressures drop, and the rate of production is controlled mostly by the capacity of the pipeline network. This means that a greater percentage of the gas reserves can be recovered, up to as much as 80% as opposed to about 50% in most oil fields. Further, production can be maintained at the same high level until the field is depleted, at which time production will suddenly drop to zero. The production profile therefore is characterized by a rapid rise to a long plateau, followed by an abrupt decline, with seasonal fluctuations in demand determining the detailed production curve (Campbell, 1997, p. 118).

In 1949, M. King Hubbert, Associate Director of the Exploration and Production Research Division of Shell Oil Company, Inc., published a paper in the journal *Science* entitled "Energy from Fossil Fuels." In this, he concluded that

> the amount [of fossil fuels] consumed up to any given time is proportional to the area under the curve of annual production plotted against time. This area may approach but can never quite equal the amount initially present. Thus we may announce with certainty that the production curve of any given species of fossil fuel will rise, pass through one or several maxima, and then decline asymptotically to zero. Hence, while there is an infinity of different shapes that such a curve may have, they all have this in common: that the area under each must be equal to or less than the amount initially present.

(Hubbert, 1949, p. 105). Since this paper was published, this peak in production is often referred to as Hubbert's Peak or Peak Oil.

Hubbert's model is schematically illustrated in Figure 14, which shows annual production from multiple oil fields over time. As noted by Hubbert (1982, p. 24), the smaller the region considered, the more irregular the production curve will be as demonstrated by the graph of Ohio oil production (Figure 11), but the general concepts of Hubert's model still apply. The total production, $P(t_1)$, from the time of first exploration ($t = 0$) up until some time t_1 is given by the area under the curve left of time t_1. In mathematical terms:

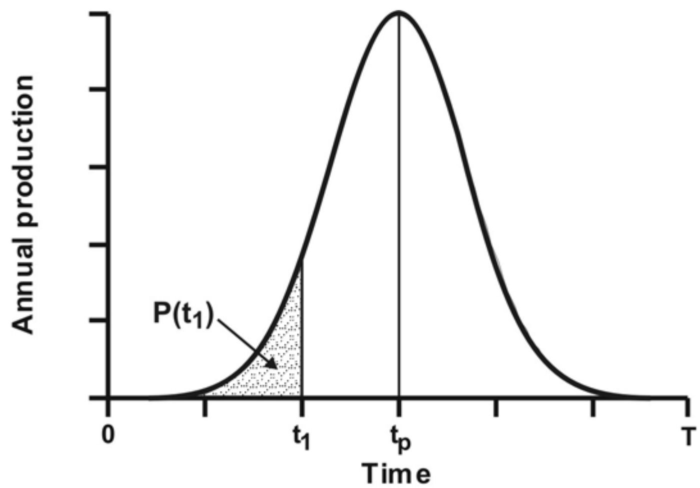

FIGURE 14. Schematic illustration of the Hubbert model for production from multiple oil fields. See text for explanation.

$$P(t_1) = \int_0^{t_1} A(t)\,dt \quad ,$$

where A(t) represents the annual production. Over its lifetime, the total production from this resource cannot exceed the ultimate recoverable reserves, URR, so that the total area under the curve must equal URR:

$$URR = \int_0^{T} A(t)\,dt \quad ,$$

where T represents the time the field is effectively depleted. For a symmetric production curve as shown in Figure 14, peak production occurs when half of the recoverable resources have been mined, so that

$$0.5 \times URR = \int_0^{t_p} A(t)\,dt \quad .$$

Hubbert repeatedly stressed that there is no *a priori* reason for the production curve to be symmetric but the U.S. data he considered suggested symmetry and his subsequent mathematical analysis (Hubbert, 1982) is based on a symmetric curve. The restriction of symmetry has since been relaxed in some studies (e.g. Wood and others, 2004), which tends to shift the production peak to the right, followed by a more precipitous decline, but otherwise does not essentially affect the basic model. For the following discussion, it is important to realize that at any time the field is operable, the ultimate recoverable reserves are equal to the production up to date, P(t), the remaining proven reserves, PR(t), and the unproven reserves, UR(t), which represents the oil that has yet to be found. Thus

$$URR = P(t) + PR(t) + UR(t) \quad .$$

Note that, whereas the terms on the right-hand side change over time, the URR is a fixed – albeit perhaps poorly known – quantity.

As the graph of Ohio oil production shows, the region under consideration needs to be sufficiently large to mask contributions from individual fields that are explored subsequently. The entire oil production in the United States constitutes a large enough sample to cancel irregularities of smaller areas, and the aggregate production curve will be smooth with a single maximum.

In 1956, Hubbert predicted that U.S. oil production would peak in the early 1970s. In subsequent publications, he updated this prediction using more up-to-date data, but the timing of peaking did not change significantly (Hubbert, 1956, 1962, 1974, 1982). The earlier predictions were based mostly on graphical interpretation and extrapolation of production curves, and it was not until 1982 that Hubbert published the mathematical foundation of his oil-production model (Hubbert, 1982).

For the next several decades after Hubbert issued his first prediction of U.S. peak oil production, his warnings fell mostly on deaf ears, until in 1971 U.S. production of crude oil indeed did peak. In the spring of 1971, Texas, as well as other oil-producing states, were producing at full capacity, leaving no room to increase production in case of an emergency (Deffeyes, 2001, p. 5). Since peaking at slightly over three billion barrels in 1971, U.S. production declined steadily to two billion barrels in 2000 (Figure 15). Increased production from the Alaskan North Slope and offshore production in the Gulf of Mexico slowed the rate of decline somewhat, but even the Alaskan fields currently in production appear to have peaked after about two decades of operation (Figure 16). To meet increasing demands, imports of foreign oil have steadily risen, interrupted in the late 1970s and early 1980s by the conflict between Iran and Iraq which resulted in declining exports from both countries (Heinberg, 2003, p. 72-73). Since 1996, U.S. imports have exceeded domestic supply (Figure 17) but it is interesting to note that in 2004, the U.S. still was the world's third top oil producer, after Saudi Arabia and Russia. Total U.S. production in 2004 was almost equal to the net oil exports of Saudi Arabia, the world's top exporter (Table 2).

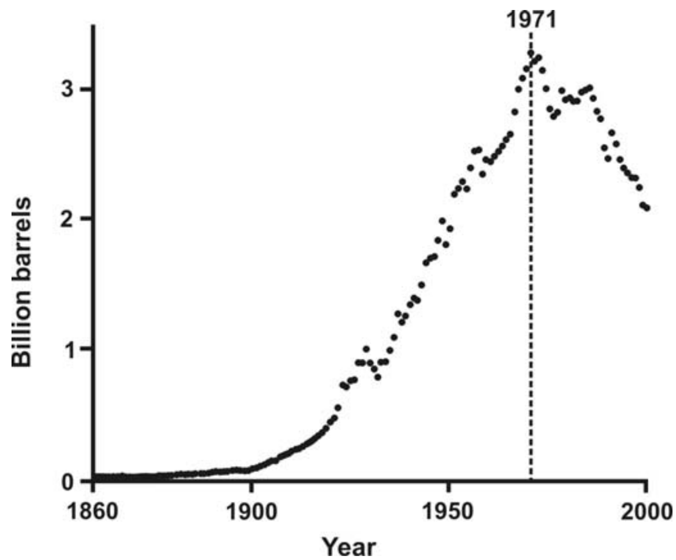

FIGURE 15. Annual production of U.S. crude oil including production from Alaska and from offshore fields. *From: Deffeyes (2001).*

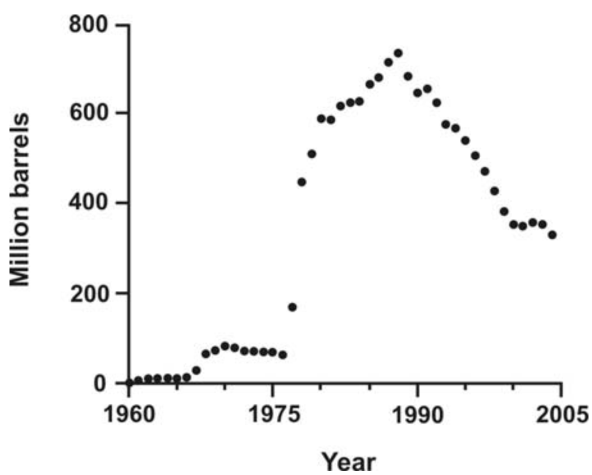

FIGURE 16. Annual production of crude oil from Alaskan oilfields. *Based on data from the U.S. Energy Information Administration.*

One consequence of the greater U.S. dependence on foreign oil is that control over the price of oil shifted to the Organization of Petroleum Exporting Countries (OPEC) which was established on September 14, 1960 through efforts by the oil minister of Venezuela, Perez Alfonso, to provide oil-producing nations with greater control over the market and price of oil (Campbell, 1997, p. 138). Up until that time, the state of Texas, through its regulatory Texas Railroad

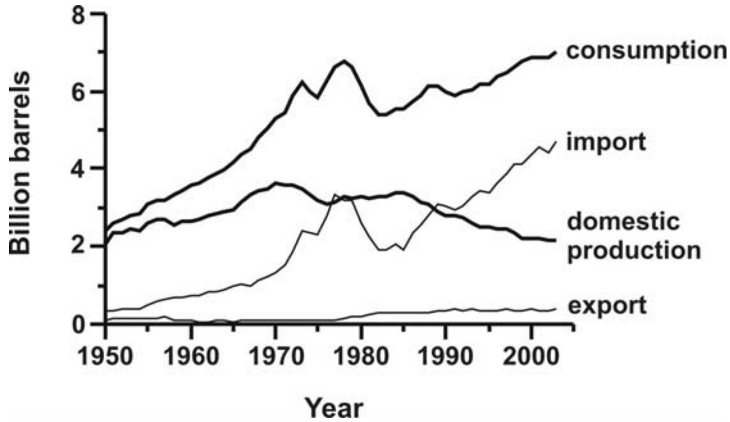

FIGURE 17. Annual U.S. domestic production of crude oil and annual imports during the second half of the twentieth century. *Based on data from the U.S. Energy Information Administration.*

Top oil producers (million barrels per day)			Top oil net exporters (million barrels per day)		
1	*Saudi Arabia*	10.37	1	*Saudi Arabia*	8.73
2	Russia	9.27	2	Russia	6.67
3	United States	8.69	3	Norway	2.91
4	*Iran*	4.09	4	*Iran*	2.55
5	Mexico	3.83	5	*Venezuela*	2.36
6	China	3.62	6	*United Arab Emirates*	2.33
7	Norway	3.18	7	*Kuwait*	2.2
8	Canada	3.14	8	*Nigeria*	2.19
9	*Venezuela*	2.86	9	Mexico	1.8
10	*United Arab Emirates*	2.76	10	*Algeria*	1.68
11	*Kuwait*	2.51	11	*Iraq*	1.48
12	*Nigeria*	2.51	12	*Libya*	1.34
13	United Kingdom	2.08	13	Kazakhstan	1.06
14	*Iraq*	2.03	14	*Qatar*	1.02

TABLE 2. Top world oil producers and net exporters for the year 2004, including all countries whose oil production exceeded 2 million barrels per day, or whose net exports exceeded 1 million barrels per day in 2004. Total oil production includes crude oil, natural gas liquids, condensate, refinery gain, and other liquids. OPEC members are in italics. *Based on data from the U.S. Energy Information Administration.*

Commission had been able to keep the price of oil steady and relatively low by increasing production when prices rose and decreasing production in times of low prices. However, in the late 1960s, despite the Commission opening many new fields, insufficient oil was produced for Texas to remain capable of regulating the market, and, instead, dominance shifted to OPEC, in particular Iran, Iraq, Kuwait, and Saudi Arabia, which by 1973 were producing 36% of the world's (Kerr, 1998).

THE WORLD OIL OUTLOOK

One has only to look at the evidence of decline and depletion of individual wells, large oil fields such as the Lima-Trenton, Trempealeau, and Clinton sandstone fields in Ohio (Figure 11), the Alaskan oil fields (Figure 16) or entire countries such as the U.S. (Figure 15), to arrive at the question "how long before world oil production will reach its peak?" The question is not *if* but *when* this peak will occur. Estimates range from as early as 1995 (Hubbert, 1981) to somewhere in the second half of the 21st century (Wood and others, 2004). The history of annual world production (Figure 18) shows a prolonged period of modest growth in annual output, followed by two or three decades of very rapid expansion; since the 1970s the growth rate has decreased to the current rate of ~2% per year increase in world production. The sharp drop in oil production in 1979 was the direct consequence of the Shah of Iran being replaced by the Islamic fundamentalist, Ayatollah Khomeini, who established a new government based on traditional Islamic values. During the ensuing Iran-Iraq conflict, production from both countries declined significantly.

Whereas it may be tempting to view the graph in Figure 18 as evidence that the world is approaching Hubbert's Peak, other political andeconomical factors need to be taken into account. As noted by Campbell (1997, p. 52),

> this fall in demand [starting in 1970] was brought about by a combination of factors. They included improvements in engine efficiency, as exemplified by the jet engine, but more than that, there was a sort of saturation in the industrial countries. You can only drive one car at the time, even if that is stationary in a traffic jam. The pattern differed from one region to another with the recent increase in Asia and Australasia being offset by an anomalous fall in the Former Soviet Union, due to its difficult economic circumstances after the collapse of communism.

However, this decrease in demand likely was temporary as developing nations continue to expand their economies.

In principle, estimating the timing of the peak in world oil production is relatively straight-forward, provided one has a good estimate of the amount of oil there is left to produce. Proven oil reserves for the entire world are estimated to be between 900 and 1000 billion barrels (Gb) (Campbell, 1997; USGS, 2000). Taking current global annual production as 25 Gb (Wood and others, 2004) a simple calculation shows that the world's known reserves will be depleted entirely in 40 years if the current consumption rate is maintained. If, as is more likely, the consumption continues to grow at a rate of 0.4 Gb/yr (2%; the current growth rate), the last drop will be extracted 32 years hence, with a peak production of 37.7 Gb/yr. If humanity were to reverse its

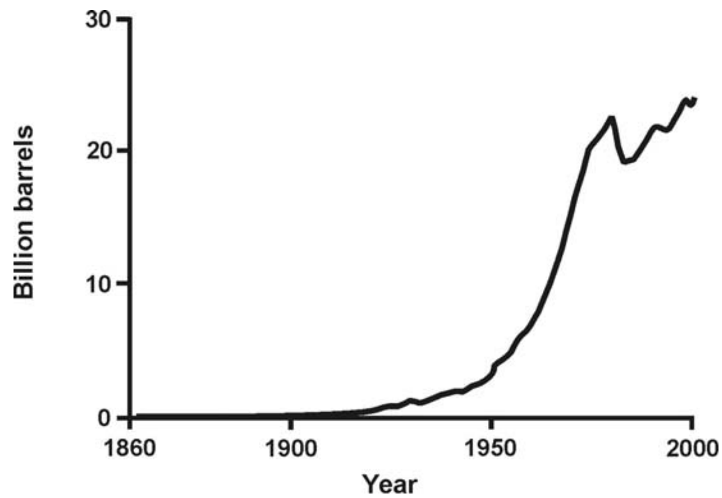

FIGURE 18. Annual world production of crude oil. *From: Deffeyes (2001).*

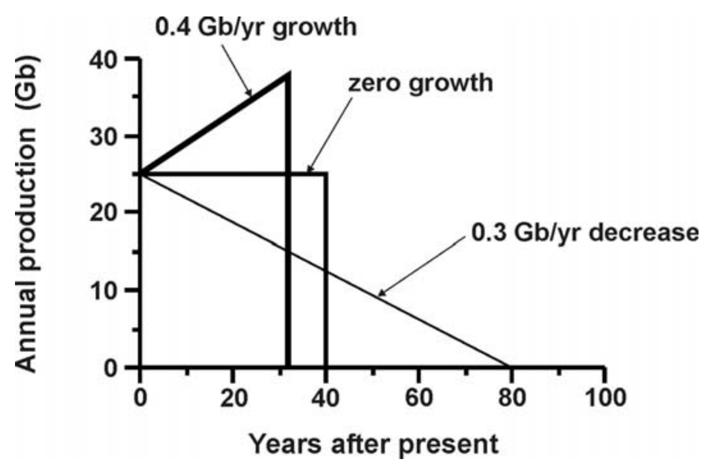

FIGURE 19. Three highly simplified scenarios for when the world's known reserves (1000 Gb) will be depleted. The medium scenario assumes production at the current level (25 Gb/yr); the high scenario assumes an annual 0.4 Gb/yr production increase, while the low scenario is based on a decrease in annual production of 0.3 Gb/yr.

dependency on oil, current supplies could last for perhaps another 80 years (Figure 19). These scenarios are not very realistic, however, as they do not take into account the natural decrease in productivity of oil fields as they become depleted. Nevertheless, each provides a simple estimate of the time involved for the three different consumption patterns.

UNPROVEN RESERVES: THE WILDCARD IN THE DECK

Significantly, not all of the world's oil reserves have been found. Even in existing fields, proven reserves may underestimate the recoverable reserves and the 2000 USGS assessment includes a significant growth of reserves in fields currently in production. Additional reserves may be found as older fields and surrounding regions are further explored, as illustrated by the history of oil discoveries in the North Sea (see Campbell, 1997, ch. 12). However, stated reserves in existing fields may also be overestimated as evidenced by the most recent downward revision of an additional 10% in the size of its proven oil and gas reserves by Royal Dutch Shell Group in early February 2005 – the fifth such reduction in slightly more than one year (Timmons, 2005). In addition, newly discovered fields add to the world's oil supply. Thus, the crucial question is "how much oil remains to be discovered?" Clearly, this question cannot be answered with precision as these reserves remain undiscovered. The usual approach is to provide some educated guess based on Hubbert's model, geological information, or some other assumption. Consequently, the issue of "unproven reserves" and the world's ultimate recoverable reserves (WURR) remains hotly contested.

The USGS World Energy Assessment Team of more than 40 geoscientists conducted extensive geological studies over a five-year period from 1995 to 2000 to arrive at an estimate for the WURR (USGS, 2000). In that study, a distinction is made between undiscovered reserves in new fields and reserve growth from fields already discovered. The mean (expected) volume of undiscovered oil reserves is estimated at 724 Gb, and reserve growth is expected to add another 674 Gb, for a total of 1398 Gb of oil yet-to-be found[8]. This estimate is significantly greater – almost an order of magnitude – than estimates based on statistical analysis of available production and discovery data.

The 2000 USGS estimate is based on a resource-assessment model developed in 1998 and referred to as the "Seventh Approximation." According to the USGS (2000, p. AM-10 – AM-11),

> the Seventh Approximation is a geology-based assessment model. The information required for estimation of undiscovered conventional resources is supplied by earth scientists who are knowledgeable about the petroleum geology of the area under consideration.

In essence, the "experts" provide a probability distribution for the number of undiscovered fields, as well as a probability distribution for the sizes of these undiscovered fields. Using a Monte

[8] Note that these numbers are slightly less than the estimates originally published (732 and 688 Gb, respectively); the updated numbers can be found in the revised summary available online at http://pubs.usgs.gov/dds/dds-060/

Carlo simulation, probability distributions for undiscovered conventional resources were then estimated. The study explicitly states that statistical projections of historical trends are not considered in the assessment (USGS, 2000, p. AM-3). The USGS report does not specify what is meant by “knowledgeable”, nor does it provide affiliations of the experts involved. It appears, however, that the pool of experts consists mostly of USGS employees, rather than being made up of international geologists who have extensive (field) experience in the regions considered, as one would have expected.

More disturbing than who the experts involved were is the way the assessment results are presented. As an example, consider the East Greenland Rift Basin off the coast of north-east Greenland. For this region, the knowledgeable Earth scientist was Mitchell E. Henry of the Denver (Lakewood) branch of the USGS. The stated 95% probability is 0 barrels, meaning there is a 95% probability of finding at least zero barrels. The 5% probability is a whopping 111,815 million barrels thus there is a 5% probability of finding a mother lode of 111,815 million barrels. From this range, a mean value of 47,148 million barrels (47 Gb) of undiscovered resources is computed for this region. As Campbell (2005, p. 234) rhetorically asks, “can we really give much credence to the suggestion that this remote place, which has so far failed to attract the interest of the industry, holds almost as much oil as the North Sea, the largest new province to be found since World War II?” Indeed, considering that much of this region has been scarcely subjected to geophysical and seismic surveys, the USGS estimate cannot be characterized as anything but wishful thinking, at best – no matter how impressed the USGS may have been with their probabilistic Seventh Approximation. Yet this “estimate” is included in the world resources estimate.

Hubbert (1982, p. 26-27, p. 31-32) also took issue with what he referred to as the “so-called geologic method of petroleum estimation.” His objections to such methods are worth reiterating here.

> Petroleum geology and geophysics, which are fundamental to petroleum exploration, comprise the entire complex of existing knowledge regarding the origin, migration, and entrapment of oil and gas, and their present modes of occurrence. This involves of necessity the most detailed knowledge that can be obtained regarding the rocks filling various sedimentary basins, their spatial distribution, and their fluid contents, water, oil, and gas. This information is acquired jointly by surface geological and geophysical mapping, but eventually in most detail from the subsurface geological information provided by wells drilled into the sediments. It is a truism of the petroleum industry that the only tool that actually discovers oil is the drill. Hence it is the record of exploratory and production drilling in a given region that provides the most reliable information available regarding the occurrence of oil and gas, and the probable quantities of these fluids that a given basin may eventually be expected to yield.
>
> However, during the last twenty years, a great deal of confusion has been introduced into the estimates of future petroleum production by the argument that “geological” methods of estimation

> must somehow be more reliable than so-called statistical methods based upon the cumulative information provided by drilling. By the advocates of this view, the scope of "geology" is seldom defined, but it apparently excludes or minimizes the importance of the information provided by drilling. The estimates obtained by these so-called geological methods during the 1960-decade for the ultimate amounts of crude oil and natural gas to be produced in the Lower-48 states and adjacent continental shelves of the United States were commonly about 600 to 650 billion barrels for crude oil and 2,500 trillion cubic feet for natural gas.
>
> ….
>
> From the foregoing discussion it should be clear that arguments over the relative superiority of the so-called geological estimates and those arrived at by other methods serve little useful purpose but can produce a great deal of confusion, especially when the geological estimates are several-fold larger than other estimates. Actually, a petroleum geologist or engineer, when studying a given region, makes use implicitly or explicitly of every kind of pertinent information that may be available. A large and significant part of this information has to be the cumulative knowledge provided by prior exploratory and production drilling.

In 2004, the cumulative U.S. production in the Lower 48 states was about 190 billion barrels, with annual production declining, so, indeed, total recoverable resources amounting to 600 Gb or more seem optimistic.

Bartlett (2000) adopted a quantitative analytical method to estimate the world's ultimate recoverable reserves, as well as the timing of peak production. In essence, he assumed that Hubbert's model can be described by a Gaussian ("bell-shaped") curve, rather than the more complex solution of the logistic growth equation used by Hubbert (1982). Gaussian curves are fully characterized by three parameters (WURR, timing of the maximum, and width or standard deviation) that can be determined by seeking the best fit with observations. The "best fit" value for WURR found by Bartlett (2000) is 1115 Gb. Clearly, this represents a considerable underestimate since the sum of production to date (784 Gb according to Campbell, 1997; 710 Gb according to USGS, 2000) and proven reserves (900 – 1000 Gb) exceeds this estimate by almost a factor of two. As noted by Bartlett (2000), this discrepancy is the consequence of world data not yet showing a long and persistent downturn in production (as do the U.S. data for which the Bartlett approach yielded better results). Thus, only data on the left flank of the production curve are used to constrain the theoretical curve, which tends to underestimate the area under the curve and hence the ultimate oil reserves.

Rather than considering annual production data, Campbell (1997) and Campbell and Laherrère (1998) investigated curves showing discovery over time. Field reserves are continuously updated and revised after the initial discovery of a field. Without adjustment, such revisions tend to distort forecasts and, according to Campbell and Laherrère (1998, p. 80-81),

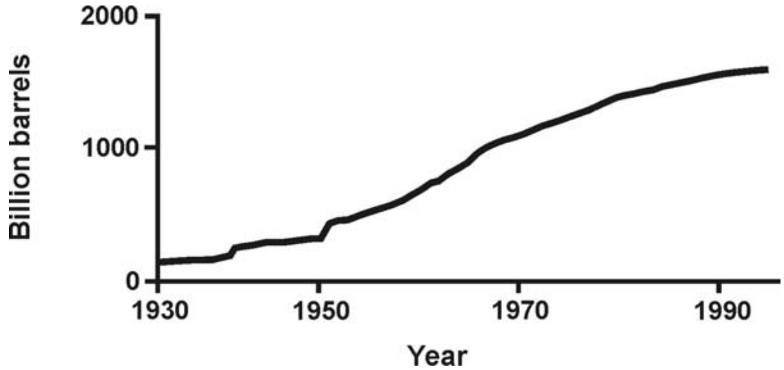

FIGURE 20. Cumulative world oil discovery, backdated to the year fields were first discovered. *From: Campbell (1997).*

> to judge accurately how much oil explorers will uncover in the future, one has to backdate every revision to the year in which the field was first discovered – not to the year in which a company or country corrected an earlier estimate. Doing so reveals that global discovery peaked in the early 1960s and has been falling steadily ever since. By extending the trend to zero, we can make a good guess at how much oil the industry will ultimately find.

Figure 20 shows the cumulative discovery of world oil reserves. Extrapolating this curve, Campbell (1997, p. 77) estimated the world's ultimate recoverable reserves of oil to be 1800 Gb, of which only 180 Gb has yet to be discovered.

A comparable analysis was conducted by Hubbert (1982) who considered the discovery rate of crude oil as a function of length of exploratory drilling for the U.S. His graphs suggest that discovery rates decrease exponentially with drilling length, so that initial drilling efforts yield the greatest discoveries but as exploration continues, further drilling yields increasingly smaller amounts of oil. This, of course, is to be expected, as no further oil can be found once all resources have been identified.

One cannot *a priori* discount the USGS (2000) estimate. Nevertheless, it is somewhat of a mystery why so little of the alleged 1420 Gb unproven reserves has been found, despite intensified exploration efforts following the oil crises of the 1970s. Around the world, oil discovery peaked during the 1960s at just under 37 Gb per year, and declined to ~7 Gb per year over the period 1990 – 1996 (Figure 21), at which point they fell *below* the production rate. Similarly, the discovery of new giant fields peaked in 1965 (Figure 22), and new finds are in smaller fields. According to a news release by IHS Energy on October 18, 2004, liquid new-field resource additions of some 13.9 billion barrels in 2003 were the fifth highest of the past decade, but only replaced half of the production during that year.[9]

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[9] Available online at: <http://www.ihsenergy.com/company/press/pressreleases/arc2004/pr_101804-trends.jsp>

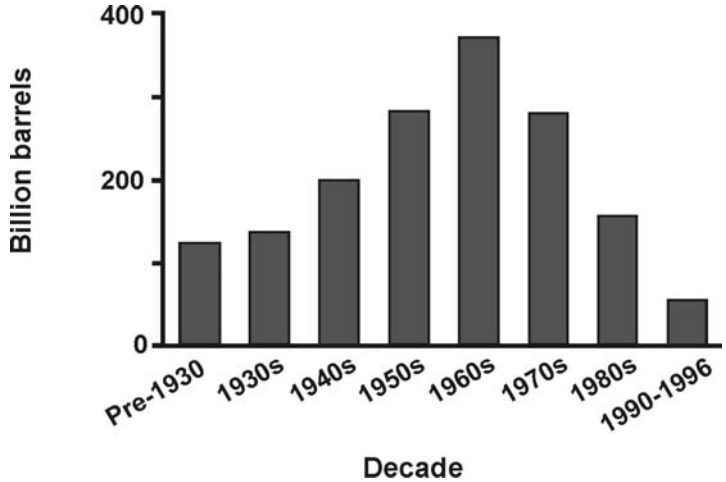

FIGURE 21. World oil discovery by decade. *From: Campbell (1997).*

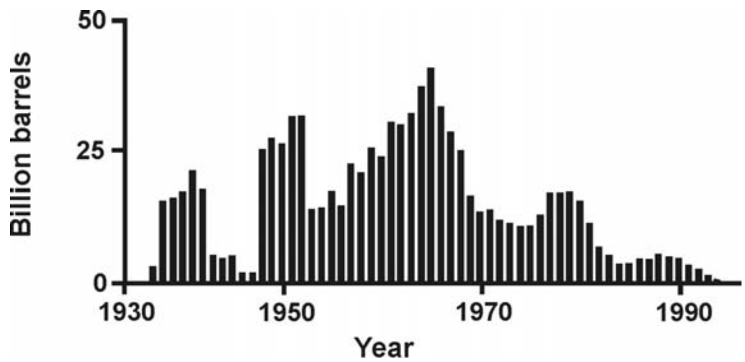

FIGURE 22. Discovery of reserves in giant oil fields (containing more than 0.5 billion barrels; reserve revisions backdated) shows a clear peak in the mid 1960s at slightly more than 35 Gb in 1965. *From: Campbell (1997).*

UNPROVEN RESERVES: HOW IMPORTANT ARE THEY?

According to the estimates of Campbell and Laherrère (1998), the world's ultimate recoverable reserves are 1800 Gb, whereas the expected mean value is 3000 Gb according to the USGS (2000) assessment. Certainly, one would expect such a large range of estimates to have an important effect on scenarios for future oil production and consumption. Or, maybe not?

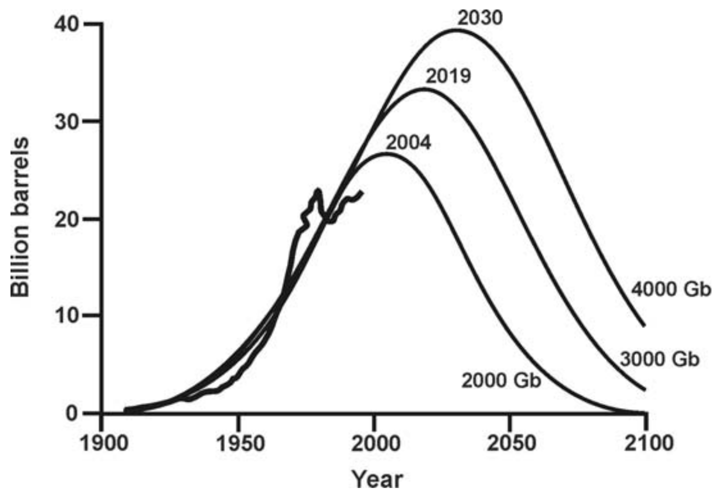

FIGURE 23. Annual production scenarios according to three Gaussian curves fitted to world oil production data (heavy curve) for three assumed values for the world's ultimate recoverable reserves (WURR). Respective year of peak production is indicated. *From: Bartlett (2000).*

Bartlett (2000) investigated how the timing of peak production is influenced by the assumed value for the WURR, assuming annual oil production can be approximated by a Gaussian curve. His results indicate that an increase in WURR from 2000 Gb to 3000 Gb delays peak time by a mere 15 years (Figure 23). Put differently: "for every new billion barrels of oil added to the estimate of the world's ultimate recoverable reserves, the date of the world peak production is delayed approximately 5.5 days!" (Bartlett, 2000).

A similar conclusion was reached in a study by the Energy Information Administration (Wood and others, 2004). That study, while in the spirit of Hubbert's analysis, differed from other studies by accounting in a quantitative manner for both demand and supply (as opposed to fitting curves based only on production data) and, more importantly, by abandoning the symmetry of the production curve and the declining trend after peak production is not assumed to be a mirror image of the production increase prior to reaching the peak. The immediate consequence of this modification of a Hubbert model is that peak production will occur at a later time, and post-peak decline will be more rapid than when symmetry is assumed (as illustrated schematically by the High and Low scenarios shown in Figure 19). To model continued world production, the EIA study merged two functional forms, the first of which extends production from historical data along a path of constant percentage growth until reaching peak production. The second function describes post-peak production decline at a constant reserves-to-production ratio, taken equal to 10. Results for the 2% annual growth scenario are shown in Figure 24, and indicate that increasing the WURR from 2248 GB to 3896 Gb (the Low and High estimates from the USGS

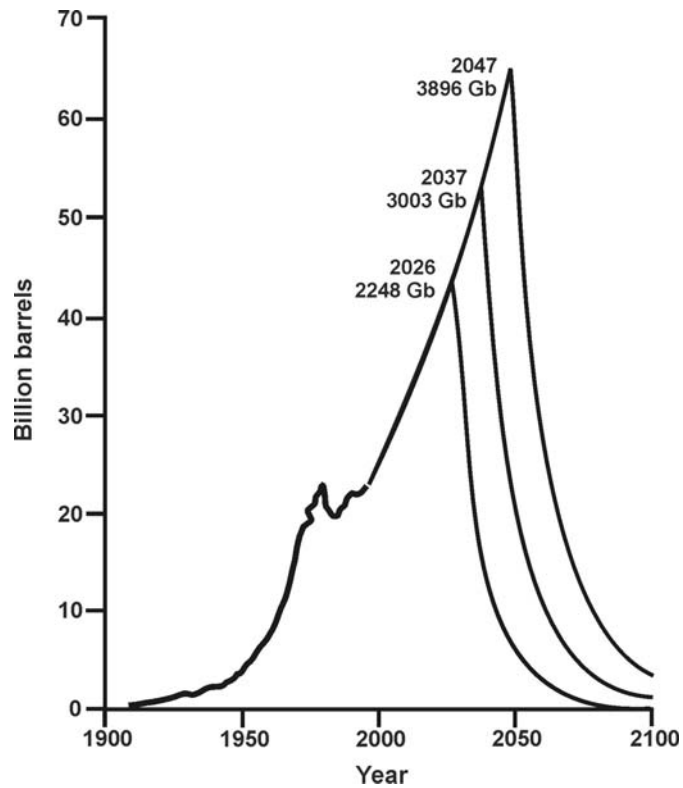

FIGURE 24. Annual oil production scenarios assuming 2% annual growth rates for three different values of the world's ultimate recoverable resources; the decline path after the indicated year of peak production is defined by a constant reserves-to-production ratio, R/P = 10. *From: Wood and others (2004).*

assessment) results in a delay in peak production of only 21 years! Note that in these scenarios the implicit assumption is made that discoveries of unproven reserves will keep pace with increased production. In view of past discoveries (Figures 20 - 22), this may, indeed, be an extremely optimistic view, as it would require discovery rates higher than those of the 1960s, and that they be sustained over almost half a century! This point is discussed in detail in the next section.

CORNUCOPIANS AT THE DOOR

While it has been almost half a century since M. King Hubbert forecast that U.S. oil production would peak in the early 1970s., and 35 years since U.S. annual production of crude oil peaked at slightly over 3 billion barrels in 1971, Hubbert's ideas continue to be challenged by what appears to be a small but vocal minority – much like the debate about anthropogenic forcings of the global climate.

According to Michael C Lynch (2003, p. 39),

> The initial theory behind what is now known as the Hubbert curve was very simplistic. Hubbert was simply trying to estimate approximate resource levels, and for the US Lower 48, he thought a bell curve would be the most appropriate form. It was only later that the Hubbert curve came to be seen as explanatory in and of itself, that is, geology requires that production should follow such a curve.

The assertion "that it was only later that the Hubbert curve became to be seen as explanatory" requires references to those articles which purport to see it as such. Otherwise, this will be viewed by serious readers as a 'hit and run' tactic, and sloppiness on the part of the writer. Furthermore, this statement also is disingenuous and demonstrates a palpable ignorance of geology and its history. Long before Hubbert, geologists had pointed out that mining production follows a pattern of boom and bust: slow initial production preceding rapid growth as readily available resources are mined, followed by peak production and slow decline (e.g. Orton, 1889; Hewett, 1929). Of course, geologic constraints are not the sole factor in driving the precise nature of the production cycle, and Hewett (1929) also discussed the importance of technology, economics, and political factors. Nevertheless, the primary driver for the cycle of mining production is the finite availability of the resource being mined. Clearly, without understanding these concepts, there would have been no reason for Hubbert to adopt a bell-shaped curve considering that the data available at the time applied to the period of rapid growth and by themselves showed no sign of an approaching peak.

Much of the criticism revolves around the logistic model adapted by Hubbert (Adelman and Lynch, 1997; Linden, 1998; Lynch, 2003; Holtberg and Hirsch, 2003). Hubbert recognized that production need not be symmetric and in his 1949 paper, he presented two possible projections both of which are asymmetric with a longer period of decline than the corresponding period of increased production. Hubbert adopted the logistics model, which yields a parabolic curve for production rate, dQ/dt, as a function of cumulative production, Q, because this symmetry was dictated by the U.S. oil production data, not because of some *a priori* assumptions. However,

> it is to be emphasized that the curve of dQ/dt versus Q does not have to be a parabola, but that a parabola is the simplest mathematical form that this curve can assume. We may accordingly regard the parabolic form as a sort of idealization for all such actual data curves, just as the Gaussian error curve is an idealization of actual probability distributions. *(Hubbert, 1982, p. 46).*

Other functional relations for resource production and depletion have been examined since, such as the Gompertz function (Moore, 1966) or the extended class of Richards functions (Wiorkowski, 1981), but none appears to offer a substantial improvement over Hubbert's logistic model when applied to existing production data. If critics wish to reject the logistics model, they should provide a credible alternative. Simply discarding Hubbert because one wishes to delay the timing of Peak Oil is unscientific.

Lynch (2003, p. 39) makes a feeble attempt to discredit Hubbert's model:

> discovery sizes tend to be asymmetric, with an early peak and a long tail. Field production often follows such a pattern as well. But production within a region is heavily influenced by the explorationists' access to territory, taxes, infrastructure, and a host of other factors, so that oil production rarely follows a bell curve, as can be seen in Campbell (2003), where only 8 of 51 non-OPEC countries appear to do so.

Michael C. Lynch would be more credible, were he thoroughly familiar with Hubbert's writings. But rather than study the original papers, Lynch appears to be relying on secondary sources. Hubbert discussed oil production in the states of Ohio (Hubbert, 1956, p. 13) and Illinois (Hubbert, 1982, p. 34-35) to demonstrate that the smaller the region, the more irregular in shape the production curve is likely to be. However,

> for large areas, such as the entire United States or the world, the annual production curve results from superposition of the production of thousands of separate fields. In such cases, the irregularities of small areas tend to cancel one another and the composite curve becomes a smooth curve with only a single principal maximum. *(Hubbert, 1982, p. 34).*

Thus, for individual countries one would indeed expect deviations from the bell curve, but for the aggregate, the production curve can be described by a bell curve, as shown in figure 8.3 in Campbell (1997). As an aside, if the bell curve is a poor approximation for production curves, the statistical probability that this curve applies to some of the non-OPEC countries would indeed be much smaller than the 16% (8 out of 51) suggested by Lynch (2003).

As for Hubbert forecasting the peak of U.S. oil production in the early 1970s, Adelman and Lynch (1997) acknowledge that Hubbert correctly predicted this peak, but wonder whether this peak was the result of resource exhaustion, or of cheaper imported oil more freely available? Similarly, Linden (1998) states without providing supporting evidence that the U.S. peak "had nothing to do with any geological factors, but was merely a rational reaction to the realities of the global oil market." So, either we are led to believe that Hubbert got incredibly lucky, or that he must have been a truly visionary economist who could forecast the global oil market almost 20 years in advance! Either possibility seems extremely unlikely.

So, how well do the Hubbert forecasts agree with production data? According to Adelman and Lynch (1997, p. 56) not very well:

> for the U.S., Hubbert in 1974 estimated URR [ultimate recoverable resources] at 170 billion bbl. Production to date has already been 170 billion bbl, proved reserves are 20 billion bbl, and annual accretions above 2 billion bbl. Discoveries continue. Output in 1996 was about twice Hubbert's forecast.

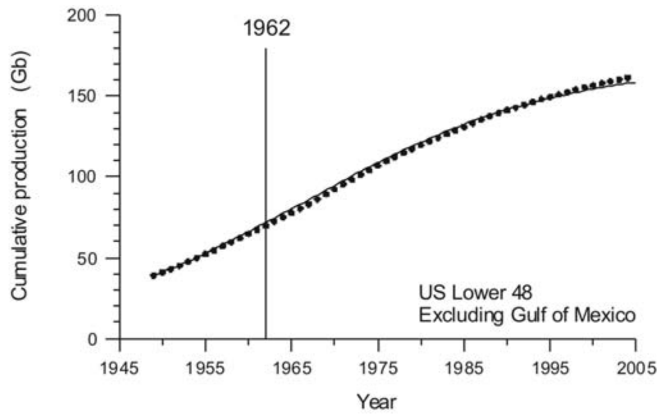

FIGURE 25. Cumulative oil production in the Lower 48 states (dots), excluding production from the Gulf of Mexico, compared with the predicted trend (solid line) obtained by Hubbert (1962) based on production data on the left of the vertical line.

A similar argument is made by Linden (1998) who estimated that potential ultimate crude oil recovery from the Lower 48 states could range from 234 billion to 314 billion barrels, which certainly was much higher than Hubbert's estimate. At first glance, these numbers appear to condemn Hubbert and his followers to eternal oblivion – that is, until one realizes that what these authors are doing is comparing apples to oranges.

Hubbert based his projections on production data for the Lower 48 states in the U.S. Up until that time, offshore production in the Gulf of Mexico (GOM) was negligible, according to data available from the Minerals Management Service (MMS)[10]. Thus, any comparison of Hubbert's projections with actual production data should be limited to the region included in Hubbert's analysis – onshore production in the Lower 48 states, and exclude the deep-water production in the Gulf of Mexico. Because GOM oil is shipped to terminals in the Gulf states – primarily Louisiana and Texas – annual production numbers for these states include this offshore production. To allow for a fair assessment of Hubbert's prediction, annual production data for the Gulf of Mexico (available from MMS) should be subtracted from the production data for the Lower 48 (available from EIA). Comparing these data with Hubbert's (1962) prediction, shows that the agreement is striking.

Figure 25 shows the Lower 48 (excluding GOM) production data, as well as the logistics curve based on ultimate recoverable resources of 170 billion barrels (Gb) and an exponential time-decay constant of 0.00687 yr^{-1}(Hubbert, 1962). In 2004, cumulative production amounted to slightly more than 161 Gb. Extrapolating the production data into the future suggests the ultimate production will be about 180 Gb, much closer to Hubbert's estimate than the optimistic

[10] http://www.gomr.mms.gov/index.html

scenarios adhered to by Michael Lynch, Henry Linden, and others. It may be noted that Adelman and Lynch (1997) were too optimistic when they stated that the GOM "is expected to make 2 million b/d by 2000" – actual production in 2000 was 1.4 million barrels per day.

It appears then that M King Hubbert was right almost 50 years ago as far as oil production in the Lower 48 is concerned. Whether or not world oil production will follow suit cannot be determined until well after the world's Peak Oil. Of course, at that time the assurance that Hubbert's model applies to the world aggregate oil production will be of little consolation for those having to face energy shortages as the present generation continues to dwindle their heritage to the next generation. Nevertheless, optimists continue to display an ostrich-like "what me – no worry" attitude.

According to Holtberg and Hirsch (2003), oil resources are infinite from the perspective of the current generation. Similarly, Linden (1998) foresees an oil-rich future with an ultimate recovery approaching 4,000 Gb. In one of the many books on the topic of oil aimed at a general audience, Matthew Yeomans (2004, p. 106) concludes, after consulting only secondary sources that

> most experts agree that we are not running out of oil – there is enough of the black stuff lying below the earth's surface to last well through the end of the twenty-first century. But worrying about how much oil is left misses the point. It is the price of oil, not how much physically remains, that will determine the future course of U.S. foreign, economic, and energy policy.

The ultimate optimists can be found among those with little or no geological background – economists like Michael C Lynch and the late Julian Simon. Adelman and Lynch (1997) state that the concept of a fixed limit is wrong, whereas Simon (1996, p. 54) argued that natural resources cannot be measured and are, therefore, not finite, that is, available in unlimited quantities. According to Simon (1996, p. 62-63),

> incredible as it may seem at first, the term "finite" is not only inappropriate but is downright misleading when applied to natural resources, from both the practical and philosophical points of view. As with many important arguments, the finiteness issue is "just semantic." Yet the semantics of resource scarcity muddle public discussion and bring about wrongheaded policy decisions.
>
> The ordinary synonyms of "finite," the dictionary tells us, are "countable" or "limited" or "bounded." This is the appropriate place to start our thinking on the subject, keeping in mind that the appropriateness of the term "finite" in a particular context depends on what interests us. Also please keep in mind that we are interested in material benefits and not abstract mathematical entities per se. (Mathematics has its own definition of "finite," which can be quite different from the common sort of definition we need here.).
>
> The quantity of the services we obtain from copper that will ever be available to us should not be considered finite because there is no method (even in principle) of making an appropriate count of it, given the problem of the economic definition of "copper," the possibility of using copper more efficiently, the possibility of creating copper or its economic equivalent from other materials, the

> possibility of recycling copper, or even obtaining copper from sources beyond planet Earth, and thus the lack of boundaries to the sources from which "copper" might be drawn. That is, one cannot construct a working definition of the total services that we now obtain from copper and that can eventually be obtained from human beings.

According to Simon, whether copper, or any other natural resource used to benefit mankind will run out in the near future is irrelevant. We are not interested in the copper itself but rather in the benefits derived from its use. So, should copper become scarce, or more precisely, economically not attractive to use (for example, because mining costs increase), scientists will find substitutes and use other materials. Thanks to human ingenuity,

> [n]atural resources have been growing more plentiful over the course of the past century, as measured by their price. The 1980s, contrary to popular belief, was no exception to this long-term trend. Indeed, thanks to the steep across-the-board declines in natural resource prices in the 1980s, many of the earth's resources today are at their lowest price ever in recorded history. Even as a growing population and a more economically developed society uses more resources than ever before, the introduction of new technologies and innovations, which make us more efficient in consuming and producing natural resources, has meant that the earth's resources have continually become less of a limit to growth over time rather than more so. *(Moore, 1995, p. 137).*

Given mankind's amazing and impressive track record, Simon and other technological optimists, believe that there is no reason to doubt that our ingenuity will not bail us out in the future. Of course, it will not be the economists who bail us out, but rather, the burden is placed on scientists and engineers. As noted by John Attarian (2002, p. 279),

> moreover, Simon egregiously telescoped into the present all possible substitutions for conventional oil, from the currently feasible to the remotely possible to the wildly fanciful (apparently with no awareness of the difference), some of which cannot be achieved in relevant quantities for decades or centuries, if at all. *At any given time*, feasible substitution is limited, so is the quantity of substitutes, so is their yield of oil.

Indeed, a cynic might pose the question whether citizens of past civilizations, such as those in Mesopotamia, Egypt, Greece, Easter Island, or the Roman empire, not to forget the Mayan culture in Central America (c.f. Diamond, 2004), were equally optimistic about their prospects for the future.

The erroneous view of unlimited resources has been refuted many times – see, for example, Georgescu-Roegen (1971; 1975) or Hardin (1993) – and suffice to say here that "indefinite" should not be confused with "infinite." Concluding from the fact that we may not be able to measure something, and therefore it must be infinite or non-finite is a clear example of a *non sequitur*, or logical fallacy.

One detail is hardly ever addressed by optimists. How much oil lies hidden beneath our feet, and in the depths of the oceans is irrelevant if we cannot find and put online these supposedly rich reserves fast enough to keep up with growing demand. Consider the projections of future oil consumption issued by the U.S. Energy Information Agency (Wood and others, 2004), which was based on the USGS assessment of world oil reserves (USGS, 2000) – results for the 2% annual growth scenario are shown in Figure 24. It is important to keep in mind the probabilities assigned to the three scenarios by the USGS – the Low scenario has a 95% probability, and the High scenario only a 5% probability – more like an oil-pipe dream if you will, despite the claim by Ahlbrandt and McCabe (2002) that “the world’s endowment of recoverable oil is estimated at about 3 trillion barrels of oil by the USGS.” Indeed, as noted, some of the alleged oil riches (e.g. in the virtually unexplored East Greenland rift zone) appear to be based on little factual information (c.f., Campbell, 2003, p. 218). And then there is the question of “reserve growth” – estimated by the USGS to add almost as much to future reserves as discoveries in new fields. Laherrère (1999) argued that, at least for the U.S., growth in reserves can be attributed to faulty reporting practices rather than to technological progress. Nevertheless, one cannot discount the possibility of large undiscovered resources remaining somewhere. However, for the High scenario shown in Figure 24 to become reality, the average rate of discovery of new oil fields has to be on the order of 22 Gb every year for the next 50 years! This amounts to finding oil deposits exceeding the size of the estimated recoverable resources in the Arctic National Wildlife Refuge (ANWR) each and every year for the next half century. In addition, reserves in existing fields have to grow accordingly and – equally important – improvements in drilling and extraction technologies will have to be made to keep production from older fields at a sufficiently high level to satisfy growing demand.

The ANWR reserves are impressive indeed, with resource estimates ranging from 15.6 to 42.3 Gb in the ground according to a 1998 USGS assessment,[11] and more resources may yet be found offshore. Impressive as 42.3 Gb may sound, only 38% of this – 16.0 Gb – is technically recoverable, according to the same USGS study. If the price per barrel of crude oil rises high enough, recovering all resources that technically can be harvested becomes economically feasible, so this would add 16.0 Gb to the U.S. reserve estimates. And, for the EIA High scenario to become reality, the equivalent of two ANWR fields has to be discovered and put into production every three years for the next half century – in addition to the above-mentioned growth in proven reserves! Interestingly, according to a news release by IHS Energy on October 18, 2004, liquid new-field reserve additions of some 13.9 Gb in 2003 were the fifth highest of the past decade.[12] The oil exploration industry has its work cut out – find more oil, and find it fast.

In summary, the “oil skeptics” have so far failed to provide convincing arguments that world oil production is not nearing its peak, and that Hubbert’s model is fatally flawed. Obfuscating the

[11] Estimates for the ANWR reserves are taken from the Arctic Power website: < http://www.anwr.org/>

[12] Available online at: <http://www.ihsenergy.com/company/press/pressreleases/arc2004/pr_101804-trends.jsp>

debate by focusing on irrelevant details, or by offering dishonest and false comparisons, or by distorting what Hubbert and others after him actually wrote, serves only one purpose – to lull the public into complacency and perpetuate the pipe dream of continued economic growth through ever-more consumer consumption. Such complacency may turn deadly if we are caught off guard by depleting oil supplies with no viable energy substitutes in place.

LIFE AFTER PEAK OIL

During the 1880s, Edward Orton, a prominent geologist and first president of The Ohio State University, was commissioned by the General Assembly of Ohio to conduct a survey of the Trenton limestone oil and gas deposits in northwestern Ohio. In his report, Orton (1889, p. 612) prophetically warned that the petroleum boom could not last long and, in several places, commented on the wasteful use of these precious resources.

> That the gas and the oil are stored products, accumulated in rocks of suitable structure to serve as reservoirs, or, in other words, that we are drawing upon a definite stock of this substance, is the only rational view to be taken of the facts involved. There was in the Findlay field originally a vast but still not an incalculable amount of gas, either dry or held in and permeating the oil that accompanies it. Upon this stock the wells are drawing. From it a given number of millions of cubic feet can be used for a given number of years, but when once exhausted there is no more possibility of its renewal in the reservoir than there is of the growth of coal in mines that have been worked out. It is in this light that the waste of these priceless accumulations ought to be regarded. The new gas fields of Ohio and Indiana have been depleted in a reckless and wanton way. They would seem to have fallen into the hands of grownup children rather than sagacious business men; of ignorant vandals rather than representatives of modern civilization. Their stores, which it has cost millions of years to gather, and which if wisely husbanded might keep the wheels of industry turning for scores of years to come, have been burned as rapidly and noisily as ingenuity could devise the means for it, and largely at the dictate of real-estate speculators, whose great object was to work up that excited and irrational state of mind in regard to investments which is called a "boom."

> It is little less than vandalism to turn this superfine fuel, in amounts aggregating many millions of [cubic] feet every day, to the commonest uses of fuel; as, for example, the burning of common brick or draining tile, or in calcining common limestone, or to be consumed in an iron mill. For such use no adequate justification exists. Neither cupidity nor stupidity should be allowed to work out these evil results. If the State were wise enough and were armed with proper power, it would surely forbid such an abuse of its priceless resources.

Some 30 years later, after most of the initial oil fields in the Midwest had been depleted, and before discovery of the large Texas reserves, George Otis Smith discussed the question "where will our children get it when American wells cease to flow?" in the February, 1920, issue of National Geographic Magazine. As Orton before him, Smith (1920, p. 192) argued that:

> Conservation touches petroleum at many points. There is need for a country-wide thrift campaign looking to the saving of this essential resource. Manpower and oil ought to be conserved at all

> stages of production and consumption by better methods in the discovery, drilling, recovery, transportation, refining, and use of petroleum and its products.
>
> Unwarranted optimism, which seems indigenous in most parts of the United States, has led both the oil industry and the public to waste this best of fuels. The program of wastage begins below the ground with only partial recovery, goes on above the ground with leakage and evaporation, and continues all along the line to the indiscriminate burning fuel oil under boilers with regard for convenience rather than for efficiency, or to the even less defensible use of petroleum for oiling our roads.
>
> In oil-field operation, in refinery practice, and in the use of oil everywhere, too often the dollar test of economy is the only one applied. The situation, however, is critical enough to demand another rule – that of taking thought of the morrow and of weighing the questions of ultimate supply and demand.

Despite the early warnings of Orton and Smith, consumption of fossil fuels has escalated over the past century, without consumer's paying much attention to how rapidly resources were being depleted. After all, when Texas oil production declined, the Middle East stepped up as the major supplier of oil. And more recently, exploration in the Arctic National Wildlife Refuge (ANWR) has been touted as the answer to reducing the dependence of the United States on imported oil. Indeed, few in government or in the general population appear to be overly concerned about upcoming oil shortages – at best, fuel-efficiency standards on gas-guzzling SUVs are advocated, but the real issues are seldom, if ever, put on the table for discussion.

As has been pointed out in many books and articles (e.g. Campbell, 2003; Deffeyes, 2001; Goodstein, 2004; Heinberg, 2003, 2004), problems for societies will not arise when the last drop of oil is extracted from the Earth, but much sooner, when world oil production peaks. Of course, after Peak Oil, there will be oil available to those who can afford to pay higher prices, and to those who physically occupy oil-producing nations, but the growing gap between supply and demand is bound to result in world-wide political strain and military conflicts as nations fight over access to dwindling resources. Further, it is important to keep in mind that oil not only fuels our cars but, quite literary, makes up the fabric of our daily lives (see Table 1). The sneakers we wear, telephones we use for communication, eyeglasses, life jackets, fertilizers used for increasing crop yields to feed the growing world population and provide bio-fuels – these are but a few of the products we use daily that are made in part or all from oil derivatives.

There are, of course, alternatives and ways to cope with "life after Peak Oil." Some may be more desirable than others (e.g., nuclear energy versus wind power) and it is not the place here to dictate future pathways. However, societies should be cognizant of what is in store for the near future. Some of us may recall the oil crises of 1973 and 1979 when OPEC countries took advantage of the supply shortage in the United States and reduced oil production: instant panic and long lines at gas stations were the result, coupled to a despair for the future of the American way of life. These past peaks were temporary and artificial. *Hubbert's Peak is a permanent reality* and the sooner societies develop strategies to transition to alternative sources of energy the better. What good is the promise of cold fusion or a viable hydrogen economy fifty years into the future if the local gas station has run out of gasoline?

Peak Oil clearly is not an isolated problem. Humanity is facing many challenges brought on by our greedy way of life: global warming, soil erosion and loss of cropland, depleting fresh-water resources, sharply rising monetary damages and personal losses from the effects of natural disasters, feeding an ever-growing population – the list goes on and on. While we may be successful in mitigating the impact of one problem – for example by converting to hybrid cars, or relying more on solar and wind energy to avoid the energy crunch after Peak Oil – these measures are band-aid solutions that do not address the root of the problem: an economic system that is based on perpetual growth.

The fundamental assumption of capitalist economies is the notion of continued growth. A healthy economy is one that is growing, that is, producing increasing amounts of goods and services that are purchased by consumers. Within this paradigm of economic thinking, it should be obvious that sustainable development is an oxymoron. Economies cannot continue to expand limitlessly. Either a saturation point will be reached in terms of consumers' buying power – perhaps when the world population stabilizes and all countries have reached the economic level of developed nations – or the world will run out of resources on which economies are founded. Whether or not the "“limits to growth” will be reached in the near future, or several centuries from now may be debatable, but at some point, societies will have to adapt to different economic and societal frameworks. According to Lester Milbrath (1989, p. 35),

> our long-range analysis of schemes to make it possible for us to grow indefinitely shows that every route eventually is blocked by some unexpected limit. No matter how hard we try to stay on our present path, we shall have no choice but to change.

A similar view is expressed by Zachary Smith (2000, p. 7),

> economic growth to the extent it is dependent on inputs from the environment, has obvious limitations. The resources for additional automobiles, washing machines, and toasters cannot continue forever – even with highly efficient recycling. Yet it is an assumption of all industrial societies, regardless of the political system they operate under, that growth based on additional inputs of resources will and should continue. In capitalist countries the profit motive drives the economy to produce and induce consumption. […] It is rational, in such a system to produce goods designed to a short or predictable life span. Although planned obsolence may not be the best way to manage finite resources, it often is a logical and rational tool in business planning.

Sustainability may be defined as the ability of an existing process to continue as is, without interruption or diminution. In this respect, many societal trends and developments are unsustainable. For example, agricultural practices have led to rates of soil erosion far exceeding the rate at which new soil is formed. Groundwater levels are falling as more water continues to be mined to meet the demands of agricultural irrigation. Costs associated with impacts of natural hazards such as hurricane Katrina, are rising almost exponentially, placing increased financial burdens on societies. Without making adjustments, these trends cannot be sustained unabated into the future. Societies can elect to continue approaches followed in the past and tackle each problem separately, or they may choose a more comprehensive approach and try to establish a sustainable society. It is becoming increasingly clear that such an approach should involve the role of the environment and, more specifically, how economic development can be maintained while preserving the environment (e.g. Redclift, 1987; Milbrath, 1989). As argued by Michael Redclift (1987, p. 102-103), this discussion should extend beyond traditional nature conservation.

> Public concern with international environmental problems has largely focused on issues of species survival and conservation, rather than sustainability. This is hardly surprising, given the failure of most international development agencies to grapple effectively with the problem of human livelihoods. Public opinion has been directed towards preserving non-human species of animals and plants in their natural habitats. It has been awakened, quite properly, to the damage which human actions have inflicted on nature. What it has not been awakened to is the damage which international development processes have inflicted on the environment from which human beings depend for their livelihood. In most developed countries over a third of the public is concerned about the extinction of plant and animal species and the depletion of world forest resources. Almost as many people whose opinions were canvassed thought that changes in the tropical environment held dangers for the climate. Clearly a link exists in people's minds between what is happening to wilderness areas and the well-being of the planet in general. However, this does not necessarily extend to the links between the conservation of biotic resources in wilderness areas, and the pursuit of sustainable development in more populated areas.

Herman Daly, long-time proponent of a "zero-growth" or steady-state economy offers three alternative visions for integrating economics and ecology (Daly, 1996, p. 11):

> First, the strategy of "economic imperialism," in which the subsystem, the economy, expands until everything is included. The subsystem becomes identical to the total system, everything is economy and everything has a price. Internalization of externalities has been carried out to the limit and nothing remains external to the economy. This seems to be the implicit strategy of neoclassical economics.
>
> The second strategy is to shrink the economy boundary to nothing so that everything is ecosystem. This I call ecological reductionism. All human valuations and choices are held to be explicable by the same evolutionary forces of chance and necessity that presumably control the natural world. Relative values correspond to embodied energy content, and economies, like ecosystems, are governed by the dictates of survival. Some follow this position to its logical conclusion, and view – or at least affect to view – human extinction as no more significant than the extinction of any other species. This seems to be the implicit strategy of those many biologists and ecologists who operate on a philosophy of scientific materialism.
>
> The third strategy is the one adopted here – to view the economy as a subsystem of the ecosystem and to recognize that while it is not exempt from natural laws, neither is it fully reducible to

> explanation by them. The human economy cannot be reduced to a natural system. There is more to the idea of value than embodied energy or survival advantage. But neither can the economy subsume the entire natural system under its managerial dominion of efficient allocation. This vision of the earth as an alchemist's centrally planned terrarium, with nothing wild or spontaneous but everything base transformed into gold, into its highest instrumental value for humans, is a sure recipe for disaster.

According to Daly (1996, p. 12), it is important to draw the boundaries of subsystems such that neither too much nor too little is included or excluded. Our most pressing need for now is, however, to stop the exponential expansion of the economic subsystem, but without falling prey to the seduction of ecological reductionism.

Whether or not technology will "save the planet" – or at least us humans inhabiting the planet – remains to be seen, but the question that needs to be asked is whether this is the way in which societies want to develop. John Ashton and Ron Laura (1999, p. 1-2)

> argue that much of what has passed for progress in our society is illusory. Motivated by an obsession with unlimited economic growth, the science of technology has been corrupted and shaped into a tool for the rape of the earth. Having confused the difference between an improved standard of living and an improved quality of life, we have unwittingly sacrificed the latter for the former. While the health and environmental risks associated with technological progress are slowly becoming recognised, the belief remains that new and improved technology will provide the way to resolve the massive ecological problems which technology has in the first place created. Against this conventional view, it will be argued here that the commitment to ever-more intensive forms of technology is stultifying and inherently disruptive of the established harmony and rhythm of nature.

Sociologist Lester Milbrath (Milbrath, 1989, p. 35) succinctly captures the essence of the debate on sustainable development in one question:

> *Do We Really Want To Grow?*

So, then, what options are available to industrial societies to deal with impending oil and gas shortages in the future? Richard Heinberg (2004) explores four principal options, namely:

Last One Standing: the path of competition for remaining resources.

Powerdown: the path of cooperation, conservation, and sharing.

Waiting for a Magic Elixer: whishful thinking, false hopes, and denial.

Building Lifeboats: the path of community solidarity and preservation.

Clearly, the sooner we recognize what our options are and make our choices wisely, the greater our chances for preserving the best of human achievement while easing towards a sustainable society.

"Our ignorance is not so vast as out failure to use what we know."

M. King Hubbert

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